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Operations Research Service
Washington, DC 20591

Civil Tiltrotor Northeast Corridor Delay Analysis

(Based on the Demand Scenario Described in *Civil Tiltrotor Missions and Applications Phase II: The Commercial Passenger Market*)

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Final Report

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Dear Colleague:

Enclosed is a copy of the report **FAA/OR-100/93/013, Civil Tiltrotor Northeast Corridor Delay Analysis.**

This report analyzes the effects of the introduction of civil tiltrotor (CTR) service on delays at major airports. The report is one in a set intended to inform senior decision makers and other interested parties of the potential effects of CTR service on National Airspace System performance. It is a limited analysis of a scenario addressing the introduction of CTR service into the Northeast Corridor of the United States using several simplifying assumptions.

A tiltrotor combines the vertical take-off and landing capabilities of a helicopter with the cruise speeds and altitudes associated with a high-performance conventional turboprop aircraft. To date, tiltrotor development has progressed furthest in the military. However, for several reasons, tiltrotor vertical capabilities could make them attractive for civilian use.

These aircraft could operate using considerably less ground space than airplanes. Due to the reduced ground space required, CTR could provide greater flexibility to passengers by enabling them to take off and land closer to their actual origins and destinations rather than limiting them to conventional airport locations. With their vertical capabilities, CTR may be able to operate without interfering with airplane flows, even in the airspace surrounding congested metropolitan airports. If CTR can operate in a non-interfering manner, they could be used to supplement airport capacity and to relieve congestion and delays.

This report documents the CTR Northeast Corridor Delay Analysis. It is based on the demand scenario described in *Civil Tiltrotor Missions and Applications Phase II: The Commercial Passenger Market*. (The delay analysis builds on this earlier market study which is referred to hereafter as the Phase II Market Study.) The Phase II Market Study assessed tiltrotor characteristics and the potential market for CTR aircraft. This delay analysis report estimates the effects, of the CTR demand scenario described in the Phase II Market Study, on delays at major airports.

Delay analysis estimates that, if CTR service were to be introduced into the Northeast Corridor in the year 2000, nationwide annual delays might be reduced by approximately 540 thousand aircraft hours per year. Sensitivity analysis shows that roughly 60 percent of these benefits can be achieved with only 25 percent of the market capture assumed in the Phase II Market Study.

The largest delay reductions would occur at congested airports where fixed-wing traffic would be reduced as a result of the introduction of tiltrotor services. However, ripple-effect delay reductions would also occur at major airports outside the Northeast Corridor. Most notably, given the Phase II Delay Analysis assumptions, the introduction of CTR services in the Northeast Corridor could reduce nationwide airport delay by 19 to 29 percent depending on the delay metric being used.

Peter V Hwoschinsky

for Richard A. Weiss
Manager, Vertical Flight Program Office

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16. Abstract

This report documents an analysis ofthe effects of the introduction of civil tiltrotor (CTR) service on airport delays. The analysis is intended as one in a set of analyses designed to provide information to senior decision makers and other interested parties on the potential effects of CTR service on National Airspace System performance. It is a limited analysis of a scenario that addresses the introduction of CTR services into the Northeast Corridor of the United States using several simplifying assumptions.

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EXECUTIVE SUMMARY

INTRODUCTION

A tiltrotor aircraft combines the vertical take-off and landing capabilities of a helicopter with the cruise speeds and altitudes associated with a high-performance conventional turboprop aircraft. To date, tiltrotor aircraft development has progressed furthest in the military. However, the vertical capabilities of tiltrotor aircraft could make them attractive for civilian use for several reasons. First, these vertical capabilities allow tiltrotor aircraft to operate using considerably less ground space than conventional fixed-wing aircraft. Also, because of their reduced ground space requirements, tiltrotor aircraft could potentially provide more flexibility to passengers by allowing them to take off and land closer to their actual origins and destinations, rather than limiting them to conventional airport locations. Finally, because of their vertical capabilities, it may be possible to operate tiltrotor aircraft so that they do not interfere with the flows of conventional aircraft, even in the airspace surrounding congested metropolitan airports. If tiltrotor aircraft can be operated in a non-interfering manner, they could be used to supplement limited airport capacity and relieve congestion and delays at busy airports in metropolitan areas.

This report documents the *Civil Tiltrotor Northeast Corridor Delay Analysis (Based on the Demand Scenario Described in "Civil Tiltrotor Missions and Applications Phase II: The Commercial Passenger Market")* performed by the MITRE Corporation's Center for Advanced Aviation System Development (CAASD). This analysis is referred to hereafter as the *Phase II Delay Analysis*. The *Phase II Delay Analysis* builds on the market study entitled *Civil Tiltrotor Missions and Applications Phase II: The Commercial Passenger Market* (National Aeronautics and Space Administration [NASA] and Federal Aviation Administration [FAA], 1991), which is referred to hereafter as the *Phase II Market Study*. The *Phase II Market Study* assessed aircraft characteristics and the potential market for civil tiltrotor (CTR) aircraft. The *Phase II Delay Analysis* estimates the effects of the CTR demand scenario described in the *Phase II Market Study* on delays at major airports. At the time of the *Phase II Delay Analysis*, the *Phase II Market Study* provided the only existing demand scenario for CTR service.

A main conclusion of the *Phase II Market Study* was that Northeast Corridor CTR service would capture part of the Northeast Corridor conventional, fixed-wing aircraft market, thus reducing the demand for Northeast Corridor fixed-wing aircraft service. Supporting data from the *Phase II Market Study* included lists of specific fixed-wing flights that were identified as candidates for CTR replacement. The flights in these lists were removed in the *Phase II Delay Analysis* to represent the reduced fixed-wing demand assumed to be associated with the introduction of Northeast Corridor CTR service. All eliminated fixed-wing flights were assumed to be replaced, or "captured," by CTR service. This situation is defined as the "Phase II Demand" scenario. The *Phase II Delay Analysis* models the Phase II Demand scenario without examining terminal area or en route airspace effects, which are the

subject of subsequent, currently ongoing analyses. In this way, the *Phase II Delay Analysis* establishes a foundation of maximum achievable delay benefits from Northeast Corridor CTR service.

At a very high level and given the assumptions described herein, the *Phase II Delay Analysis* demonstrates that the hypothesized reduction of fixed wing demand due to the introduction of civil tiltrotor service will reduce airport delays. This analysis shows that if CTR service is introduced into the Northeast Corridor in the year 2000, nationwide annual delays can be reduced by approximately 20 to 30 percent. Sensitivity analysis shows that even if fixed wing demand were reduced by only 25 percent of the amount that is assumed in this analysis, approximately 60 percent of those delay reductions would still be realized.

This *Phase II Delay Analysis* is not intended to stand alone. It is one in a set of analyses designed to provide information to senior decision makers and other interested parties on the potential effects of CTR service on National Airspace System (NAS) performance. (In this report it is assumed that the reader has some familiarity with the operation of the NAS.) The *Phase II Delay Analysis* is a limited analysis of a scenario that addresses the introduction of CTR service into the Northeast Corridor of the United States using several simplifying assumptions.

All key assumptions made for the *Phase II Delay Analysis* were jointly developed by the Vertical Flight Program Office (VFPO) of the FAA's Research and Development Service, the System Analysis Division of the FAA's Operations Research Service, and CAASD. In summary, the three major simplifying assumptions of the *Phase II Delay Analysis* are:

1. Providing Northeast Corridor CTR service will reduce the demand for Northeast Corridor fixed-wing aircraft service. This reduced demand is modeled by removing the fixed-wing flights identified as candidates for CTR replacement in the *Phase II Market Study*.

2. The capacity or "slots" made available at airports by the reduction in fixed-wing demand would not be refilled. No new fixed-wing demand was assumed to surface in response to the newly available airport capacity. Implicit in this assumption is that airline response (e.g., scheduling additional flights or adjusting schedules of remaining flights) to CTR market capture has not been modeled.

3. CTRs would operate independent of fixed-wing aircraft. CTRs were assumed to operate in an independent vertiport/airspace network and not interact with fixed-wing aircraft on the airport surface, or in terminal or en route airspace.

These are important simplifying assumptions that should be kept in mind when considering the results of this analysis. The results may be very sensitive to these assumptions. The assumptions are admittedly limiting, but they suffice for the intended preliminary nature of the analysis and are acceptable if they are considered in the context of the VFPO's overall

work plan for analysis of CTR. Several additional analyses are on-going and planned. Four of them have been designed to explore the sensitivity of the simplifying assumptions made in the *Phase II Delay Analysis* and are described in the following paragraphs.

The Volpe National Transportation Systems Center (VNTSC) is undertaking an economic evaluation of the market potential for CTR aircraft. VNTSC's work will provide estimates of CTR market capture based on a methodology similar to that used in their previous Department of Transportation (DOT) work on high-speed ground transportation. This will provide additional demand scenarios that are consistent with other DOT analyses. The *Phase II Delay Analysis* estimates delay savings based on the *Phase II Market Study* demand scenario. A follow-on delay analysis is planned, similar to the *Phase II Delay Analysis* but using the VNTSC results, thus addressing the impact of assumption one.

The FAA Technical Center (FAATC) has recently completed an analysis of the sensitivity of the delay results of the *Phase II Delay Analysis* to demand scenarios which represent a reduced market potential for CTR aircraft. This is equivalent to assuming either a smaller market capture (thus addressing the sensitivity of the delay results to assumption one) or partial refilling of "captured" slots by fixed-wing flights (thus addressing the sensitivity of the delay results to assumption two). The key finding of the sensitivity analysis is that a substantial portion of the *Phase II Delay Analysis* delay savings are realized even if the market capture is assumed to be much smaller, or, equivalently, if a substantial portion of the slots are refilled. A more detailed summary of the sensitivity analysis findings is included in the Results section of this report.

Two studies are currently underway at FAA and CAASD to assess the effects of CTR aircraft on the terminal and en route airspace environments by explicitly modeling CTR aircraft in terminal and en route airspace. Together, these two studies address assumption three.

The En Route Airspace analysis will examine the simplifying assumption that CTR aircraft would not interact with fixed-wing aircraft in en route airspace. The purpose of the analysis is to assess the effects of Northeast Corridor CTR aircraft service on en route airspace loads. This analysis requires explicitly modeling the tiltrotor aircraft flights that replace the conventional fixed-wing flights that were removed in the *Phase II Delay Analysis*. (Because of differences in aircraft sizes, there is on average a replacement of approximately 1.2 CTR flights for each fixed-wing flight removed.) The CTR replacement flights will be assigned routes and modeled explicitly in the en route airspace. Year 1990 and year 2000 baseline and replacement scenarios will be analyzed with a conservative assumption regarding weather conditions.

The Terminal Airspace analysis will address the simplifying assumption that CTR aircraft would not interact with fixed-wing aircraft in terminal area airspace of the NAS. The purpose of this analysis is to investigate the viability of constructing independent approach and departure routes for CTR aircraft that do not conflict with the standard approach and departure routes for fixed-wing aircraft. The New York to Boston corridor has been chosen

for demonstrating proof-of-concept CTR terminal airspace routes. This analysis is being performed in coordination with FAA headquarters and field personnel.

The VFPO is involved in a number of other CTR-related activities, including the following:

- Terminal Instrument Procedures (TERPS) development for CTR
- Implementation of a noise research and development plan addressing key CTR noise requirements and projects
- Development of planning guidelines for vertiports/large heliports that will handle tiltrotor aircraft and other large rotorcraft

The purpose of the *Phase II Delay Analysis* is to help provide a quantitative foundation for decisions regarding investment in CTR aircraft technology and the infrastructure required to support CTR technology and incorporate it into the national transportation system. This analysis establishes a baseline of maximum achievable delay benefits from Northeast Corridor CTR service by quantifying the effects of the reduction in fixed-wing air carrier demand associated with the introduction of Northeast Corridor CTR service on delays and the associated costs using the best available demand scenario for CTR at the time. A limiting set of simplifying assumptions was used in this analysis. But, since the benefits were found to be large enough in the Northeast Corridor, further detailed investigation is justified to examine the initial simplifying assumptions and other possible scenarios that may be based on more reliable and recent information as it becomes available.

METHODOLOGY

The methodology used in the *Phase II Delay Analysis* consists of a four phase process using the National Airspace System Performance Analysis Capability (NASPAC) Simulation Modeling System (SMS), as illustrated in figure ES-1.

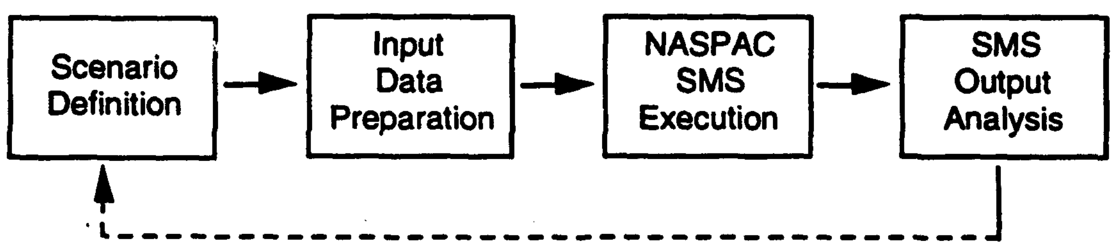

Figure ES-1. An Overview of the *Phase II Delay Analysis* Methodology

In the scenario definition phase, scenarios and a timeframe appropriate for the analysis are selected. Two scenarios are defined: a "baseline" scenario that represents the NAS without CTR service and a "removal" scenario that represents the NAS with CTR service in the Northeast Corridor. In the removal scenario, all of the fixed-wing flights identified in the *Phase II Market Study* as candidates for CTR replacement are removed and assumed to be replaced by CTRs. This is defined as a "Phase II Demand" scenario. Two timeframes were selected: 1990, which is the timeframe of the supporting data from the *Phase II Market Study*, and 2000, which (according to the *Phase II Market Study*) is the target year for introducing Northeast Corridor CTR service.

In the input data preparation phase, relevant data sources for the analysis (such as airport capacity and air carrier demand data) are identified and data are prepared for input to the NASPAC SMS.

In the NASPAC SMS execution phase, the SMS is used to generate results for each scenario and timeframe to be analyzed.

Finally, in the SMS output analysis phase, the results from the baseline and removal scenarios are compared. Although this comparison is done for both 1990 and 2000, the main focus of the analysis is the year 2000. The differences in delays between the baseline and removal scenarios provides an estimate of the maximum achievable delay savings that could accrue to the NAS as a result of fixed-wing demand reductions due to the introduction of commercial CTR aircraft service in the Northeast Corridor. These delay savings are analyzed in aggregate for all airports in the NAS, as well as separately for corridor airports (7 major airports in the Northeast Corridor), feeder airports (69 airports that are located within 500 miles of a corridor airport and have scheduled flights that directly connect to corridor airports), and other airports (airports other than corridor and feeder airports). All of the fixed-wing flights that are removed in the removal scenario are removed from corridor and feeder airports; no flights are removed from other airports. The cost savings associated with the delay savings for all airports, taken in aggregate, are also estimated.

RESULTS

In the interest of brevity, only year 2000 results are included in the Executive Summary. Section 3 of the full report contains results for both 1990 and 2000.

Figure ES-2 shows the year 2000 delay results for the baseline and removal scenarios in terms of two distinct delay metrics: technical delay and effective arrival delay. Technical delay, shown on the left side of the figure, is defined as the delay incurred by an aircraft while waiting to use a busy air traffic control (ATC) system resource. Effective arrival delay, shown on the right side of the figure, is defined as the difference between the time an aircraft arrives at its gate in the simulation and the aircraft's scheduled arrival time. Thus, effective arrival delay is a measure of passenger-perceived lateness. It includes the "ripple effect"

caused by an aircraft whose lateness on one leg of its itinerary may affect its arrival time on a later leg. It also includes built-in schedule delay and is highly dependent on airline scheduling practices.

The pairs of bars in each graph in figure ES-2 show the delay results for the baseline and removal scenarios side-by-side. The first (leftmost) pair of bars in each graph shows results for all airports in the NAS. Those results are then divided among the second, third, and fourth pairs of bars which correspond to corridor airports, feeder airports, and other airports, respectively. The parenthetical numbers above each pair of bars indicate the *decreases* in delay between the baseline and removal scenarios in thousands of aircraft hours per year. The percentage numbers indicate the percent decreases in delay between the baseline and removal scenarios.

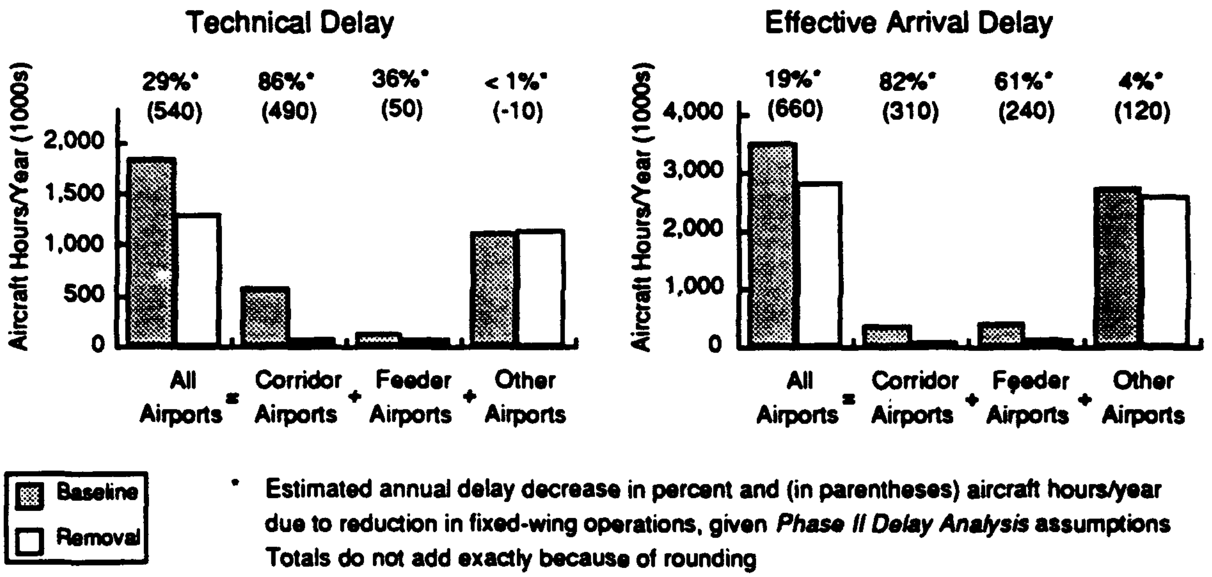

Figure ES-2. Overview of Year 2000 Delays

As shown in figure ES-2, the technical delay savings for all airports in the year 2000 were estimated to be approximately 540 thousand aircraft hours per year or approximately 29 percent. The seven corridor airports, which account for a significant portion (about 32 percent) of the technical delays for all airports in the United States in the baseline scenario, experienced the majority (490 thousand aircraft hours per year or 91 percent) of this technical delay savings. A smaller amount (50 thousand aircraft hours per year or nine percent) of the total airport technical delay savings was experienced at the feeder airports.

At other airports, where no flights were removed, technical delay was essentially unchanged between the baseline and removal scenarios.

The effective arrival delay savings for all airports in the year 2000 were estimated to be approximately 660 thousand aircraft hours per year or approximately 19 percent. The corridor airports experienced less than half (310 thousand aircraft hours per year or 47 percent) of this effective arrival delay savings. A significant amount (240 thousand aircraft hours per year or 36 percent) of the total airport effective arrival delay savings was experienced at the feeder airports. A significant effective arrival delay savings (120 thousand aircraft hours per year or 18 percent) was also experienced at other airports where no flights were removed. This effective arrival delay savings was experienced at other airports because some of the delay savings experienced at the corridor and feeder airports rippled through the NAS to reduce effective arrival delays at the other airports as well. The effective arrival delay savings at other airports tend to be concentrated at the largest airports which are well connected via flight itineraries with the Northeast Corridor. For example, in 2000, effective arrival delays were reduced by 15% at Miami, 8% at Chicago O'Hare, 17% at Atlanta, and 13% at Denver.

Corresponding to the technical delay and effective arrival delay metrics are two associated cost metrics: aircraft operational delay costs and passenger delay costs, respectively. The 2000 operational delay costs were reduced by $700 million from a baseline of $2,100 million. The 2000 passenger delay costs were reduced by $1,000 million from a baseline of $4,200 million.

Sensitivity Analysis

The CTR Phase II Demand scenario, taken from the *Phase II Market Study*, assumes large fixed-wing demand reductions within the markets considered (described in detail in appendix B); 58% of scheduled corridor flights and 75% of scheduled feeder flights were identified as candidates for CTR replacement. The sensitivity analysis, which has recently been completed by the FAA Technical Center, assessed the sensitivity of the *Phase II Delay Analysis* results to reduced market capture rates. The sensitivity analysis was conducted based on the *Phase II Delay Analysis* experimental design and data described in this report.

Summary results of this sensitivity analysis for the year 2000 are shown in figure ES-3. The *Phase II Delay Analysis* has identified two points on these curves—0% market capture (baseline demand) and "Phase II" market capture. The sensitivity analysis determined three more points on the curves: 25%, 50%, and 75% of the Phase II market capture rate (as defined in the *Phase II Market Study*).

The key finding is that a substantial portion of the *Phase II Delay Analysis* delay savings are realized even if the market capture rate is assumed to be much lower than that used in the *Phase II Delay Analysis*. As shown in figure ES-3, between one-half and two-thirds of the

delay savings are realized if market capture is reduced to a level of only one-fourth of that assumed in the *Phase II Delay Analysis*. If the market capture is one-half of that used in the *Phase II Delay Analysis*, the delay savings are approximately 80 percent of the *Phase II Delay Analysis* delay savings.

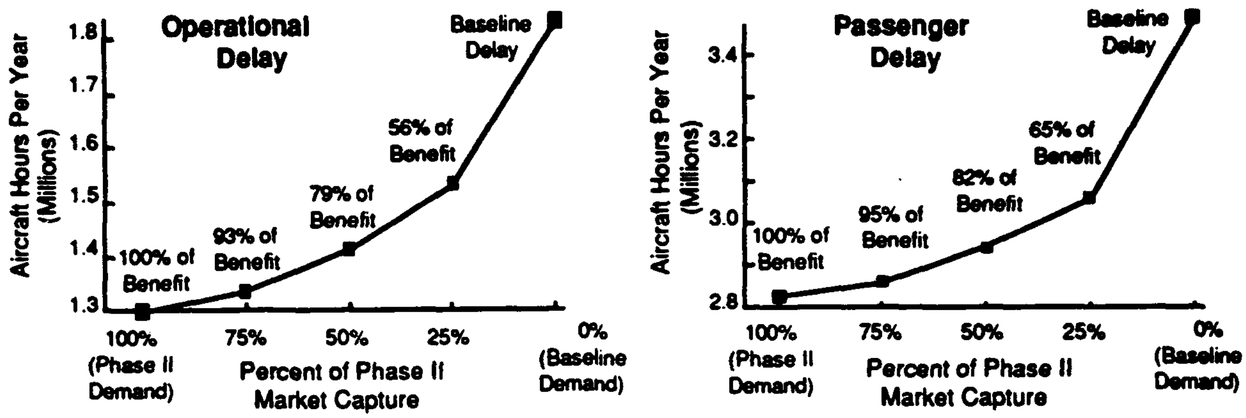

Figure ES-3. Results of Sensitivity Analysis for Year 2000

SUMMARY

The following paragraphs highlight the analysis results in the context of the *Phase II Delay Analysis* assumptions. This analysis serves as a foundation for a series of on-going, as well as planned analyses, to further quantify the potential benefits of the introduction of CTR service in the Northeast Corridor by addressing the *Phase II Delay Analysis* assumptions. These other analyses were briefly summarized in the Introduction.

Not surprisingly, the largest delay reductions tended to occur at congested airports that have large numbers of flights removed. For example, the three corridor airports that showed the largest delay reductions due to the introduction of CTR service were also the three corridor airports that had the greatest percentage of their scheduled air carrier flights removed in the modeled removal scenario (i.e., Boston Logan with 52% CTR market capture, LaGuardia with 38% CTR market capture, and Philadelphia with 35% CTR market capture). Nevertheless, ripple-effect delay reductions did occur at major airports outside the Northeast Corridor, such as Chicago O'Hare, Atlanta Hartsfield, Denver, Los Angeles, Dallas-Fort Worth, and Miami, *where no flights were removed.* Figure ES-4 shows the airports with the largest delay reductions.

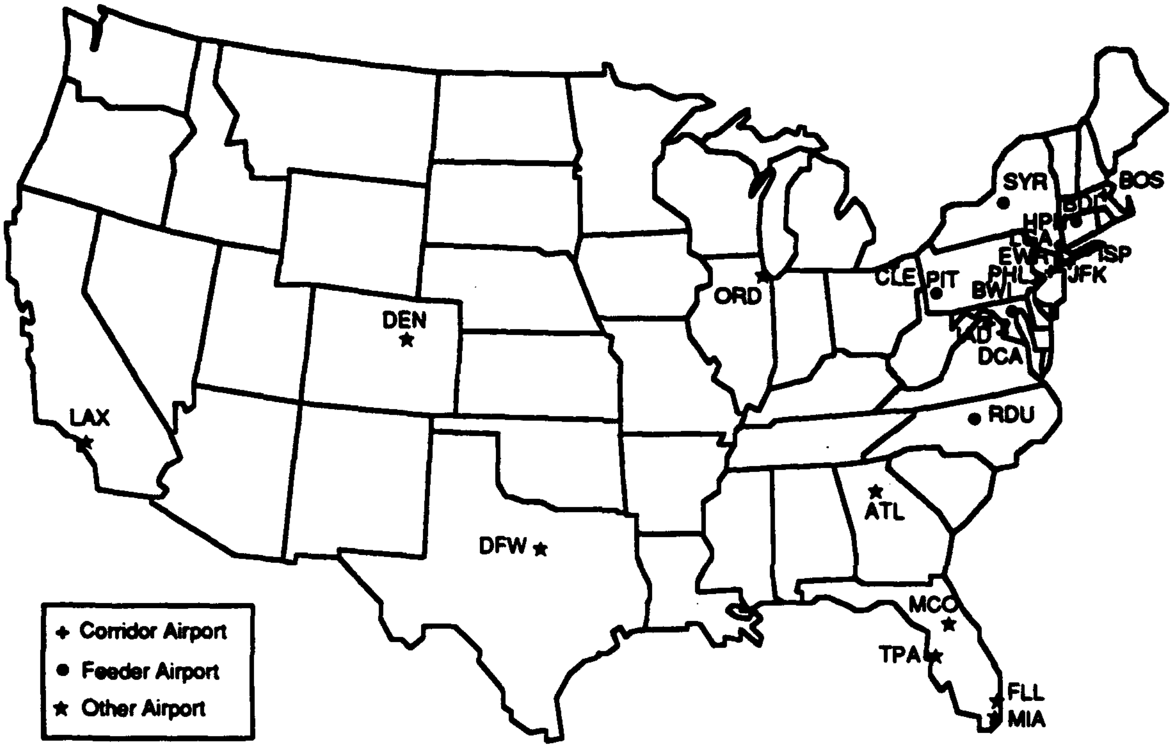

Figure ES-4. Airports with Largest Delay Reductions

The maximum achievable delay benefits due to CTR service, in terms of technical delay and effective arrival delay, are summarized in table ES-1. The two middle columns show percent technical delay and effective arrival delay reductions for the year 2000. The rightmost column provides a context or framework in which to interpret these delay reduction results by indicating the percent of the total number of all flights (including scheduled and unscheduled flights) removed in each airport category; note that only scheduled flights were actually removed. There is a strong relationship between airport demand and airport technical delay, with the largest delay reductions occurring at the corridor airports, where the largest demand reductions occur. Similarly, moderate technical delay reductions occur at the feeder airports where moderate demand reductions occur. Negligible *technical delay* reductions occur at all other airports (airports other than the corridor and feeder airports) where no flights are removed. In terms of *effective arrival delay*, however, reductions occur at other airports (third row, third column, table ES-1) *outside* the corridor and feeder network where *no* flights

are removed. The three "other" airports outside the corridor and feeder network with the largest effective arrival delay reductions in aircraft-hours per year are Miami International, Chicago O'Hare, and Atlanta Hartsfield in 2000. Most notable, perhaps, is the "bottom line" or bottom row of table ES-1, where it is shown that, given *Phase II Delay Analysis* assumptions, introduction of CTR service could reduce nationwide airport delay from 19% to 29% depending on the delay metric being used.

Table ES-1. Summary of Percent Delay Reductions Due to CTR in 2000

Airport Category	Technical Delay Reductions in 2000	Effective Arrival Delay Reductions in 2000	*Percent of All Flights Removed*
Corridor Airports	86%	82%	*29%*
Feeder Airports	36%	61%	*10%*
Other Airports	<1%	4%	*0%*
All Airports	29%	19%	*3%*

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SECTION 1

INTRODUCTION

1.1 BACKGROUND

A tiltrotor aircraft combines the vertical take-off and landing capabilities of a helicopter with the cruise speeds and altitudes associated with a high-performance conventional turboprop aircraft. To date, tiltrotor aircraft development has progressed furthest in the military. However, the vertical capabilities of tiltrotor aircraft could make them attractive for civilian use for several reasons. First, these vertical capabilities allow tiltrotor aircraft to operate using considerably less ground space than conventional fixed-wing aircraft. Also, because of the reduced ground space requirements, tiltrotor aircraft could potentially provide more flexibility to passengers by allowing them to take-off and land closer to their actual origins and destinations, rather than limiting them to conventional airport locations. Finally, because of their vertical capabilities, it may be possible to operate tiltrotor aircraft so that they do not interfere with the flows of conventional aircraft, even in the airspace surrounding congested metropolitan airports. If tiltrotor aircraft can be operated in a non-interfering manner, they could be used to supplement limited airport capacity and relieve congestion and delays at busy airports in metropolitan areas.

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defined as the "Phase II Demand" scenario. The *Phase II Delay Analysis* models the Phase II Demand scenario without examining terminal area or en route airspace effects, which are the subject of subsequent, currently ongoing analyses. In this way, the *Phase II Delay Analysis* establishes a foundation of maximum achievable delay benefits from Northeast Corridor CTR service.

This is one in a series of analyses designed to assess the feasibility and potential benefits of CTR service; it is not intended to stand alone. The *Phase II Delay Analysis* is a limited analysis of a scenario that represents the introduction of Northeast Corridor CTR service. This analysis is based on several simplifying assumptions. Several additional analyses are underway to examine the sensitivity of the *Phase II Delay Analysis* results to these assumptions. These additional analyses are described in section 5, Next Steps.

1.2 SCOPE

This report documents the *Phase II Delay Analysis*, including the methodology, results, and conclusions. It also describes follow-on analyses designed to address some of the key assumptions made in this analysis. Significant simplifying assumptions have been made in this work, which are addressed in these separate analyses. Thus, this report is not intended to stand alone. Instead, it should be considered as one in a series documenting a set of interrelated analyses.

1.3 PURPOSE

The purpose of the *Phase II Delay Analysis* is to help provide a quantitative foundation for decisions regarding investment in CTR aircraft technology and the infrastructure required to support that technology and incorporate it into the national transportation system. The *Phase II Delay Analysis* is not intended to stand alone. It is one in a set of analyses which are designed to provide information to senior decision makers and other interested parties on the potential effects of CTR service on National Airspace System (NAS) performance. (In this report it is assumed that the reader has some familiarity with the operation of the NAS.)

This *Phase II Delay Analysis* establishes a baseline of maximum achievable delay benefits from Northeast Corridor CTR service by quantifying the effects of the reduction in fixed-wing air carrier demand associated with the introduction of Northeast Corridor CTR service on delays and the associated costs using the best available demand scenario for CTR at the time. A limiting set of simplifying assumptions was used in this analysis. But, since the benefits were found to be large enough in the Northeast Corridor, further detailed investigation is justified to examine the initial simplifying assumptions and other possible scenarios that may be based on more reliable and recent information as it becomes available.

This analysis serves as a foundation for a series of on-going, as well as planned, analyses designed to further quantify the potential benefits of the introduction of CTR service in the Northeast Corridor by addressing the *Phase II Delay Analysis* assumptions. These other analyses are briefly described in section 5. For example, another delay analysis that will be based on the results of an ongoing new study of CTR market potential is planned and two analyses are currently underway to address the effects of CTR service on airspace congestion. Additionally, an analysis of the sensitivity of the delay results of the *Phase II Delay Analysis* to demand scenarios which represent reduced market potential for CTR service has recently been completed. A summary of the sensitivity analysis findings have been included in section 3.4 of this report.

1.4 METHODOLOGY

The primary tool used in performing this analysis is the National Airspace System Performance Analysis Capability (NASPAC) Simulation Modeling System (SMS). The analysis methodology consisted of defining scenarios, preparing input data, executing runs of the NASPAC SMS, and analyzing the results. This methodology is described in more detail in section 2 of this report. Appendix C contains a description of the NASPAC SMS.

1.5 AUDIENCE

This report is primarily intended for decision makers who are involved in the management of CTR and related programs. It will also be of interest to individuals who have a general interest in the CTR concept. It is assumed that the reader has some familiarity with the operation of the NAS.

1.6 TERMS AND CONCEPTS

This section contains the definitions of terms that are used in this analysis.

> **Phase II Demand Scenario:** a situation in which all scheduled fixed-wing flights identified in the *Phase II Market Study* as candidates for CTR replacement are removed and assumed to be replaced by CTR service; the CTR replacement flights are not explicitly modeled in the *Phase II Delay Analysis*.

Figure 1-1 shows the Northeast Corridor. The following five definitions pertain to the Northeast Corridor:

> **Northeast Corridor:** includes only corridor airports and vertiports (defined below) shown in figure 1-1.

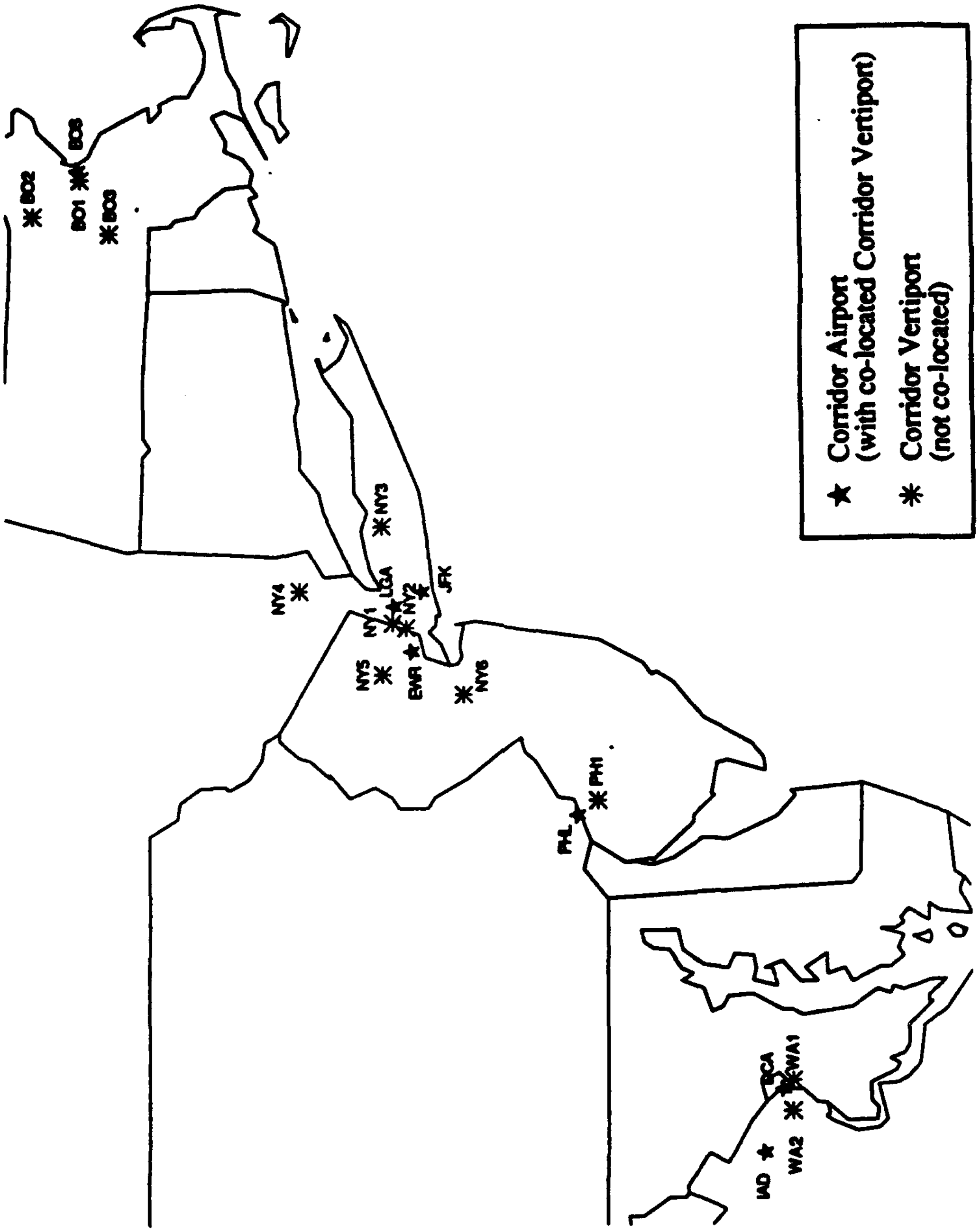


Figure 1-1. Northeast Corridor: Corridor Airports and Vertiports

Corridor Market: the passenger market of air travelers who fly within the Northeast Corridor.

Corridor Airports: the seven major Northeast Corridor airports that were defined in the *Phase II Market Study* and considered in the *Phase II Delay Analysis* (see table 1-1 and figure 1-1). It is assumed that a vertiport is located at each Corridor airport to accommodate CTR feeder flights.

Table 1-1. Corridor Airport Names and Identifiers

Airport Name	Airport Identifier
Boston Logan International	BOS
Washington National	DCA
Newark International	EWR
Washington Dulles International	IAD
John F. Kennedy International	JFK
La Guardia	LGA
Philadelphia International	PHL

Corridor Vertiports: Nineteen vertiports are located in the Northeast Corridor. Twelve of these vertiports are strategically located in the Northeast Corridor high-density travel population centers, including three in the Boston area, six in the New York area, one near Philadelphia, and two in the Washington DC area. The other seven vertiports are co-located with the 7 corridor airports. The corridor vertiports were defined in the *Phase II Market Study;* the vertiport locations depicted in figure 1-1 are based on data available as of June, 1993.

Corridor Flights: flights that have both their origin and destination within the Northeast Corridor (e.g., a flight from EWR to BOS); flights that service the corridor market.

Figure 1-2 expands the geographical range of figure 1-1 to include airports and vertiports that service the feeder market. The feeder market contains airports that are located within a 500 mile radius of the corridor airports. It extends as far north as northern Maine and as far south as South Carolina. The following four definitions pertain to the feeder market:

Feeder Market: the passenger market of air travelers who fly to the Northeast Corridor airports or vertiports from the feeder airports or vertiports, or vice versa.

Feeder Airports: 69 airports that were identified in the *Phase II Market Study*. They are located within 500 miles of a corridor airport and have flights that directly connect to corridor airports. For the purposes of this analysis, they are assumed to have co-located vertiports.

Feeder Vertiports: vertiports that are co-located with feeder airports and have flights that directly connect to corridor vertiports.

Feeder Flights: flights with their origin within the Northeast Corridor and their destination at a feeder airport or vertiport, or vice versa (e.g., a flight from ALB to BOS, or a flight from BOS to ALB); flights that service the feeder market.

For the purpose of this analysis, airports that are not directly involved in Northeast Corridor CTR service are called "other" airports. This definition is included because some of the delay benefits achieved at corridor and feeder airports as a results of CTR market capture ripple through the NAS and benefit other airports.

Other Airports: airports (within the continental United States) other than corridor or feeder airports; airports not shown in figure 1-2.

Figure 1-3 summarizes the terms and concepts that were defined for use in this analysis and described above. The Northeast Corridor consists of corridor airports and vertiports. Corridor flights move passengers within the Northeast Corridor. Fixed-wing corridor flights fly between the seven corridor airports. CTR corridor flights fly between the 12 non-co-located corridor vertiports. Feeder flights move passengers into or out of the Northeast Corridor. They have either their origin or destination, but not both, within the Northeast Corridor. Fixed-wing feeder flights fly between feeder airports and seven corridor airports. CTR feeder flights fly between co-located feeder vertiports and seven co-located corridor vertiports. Other airports are airports other than corridor or feeder airports.

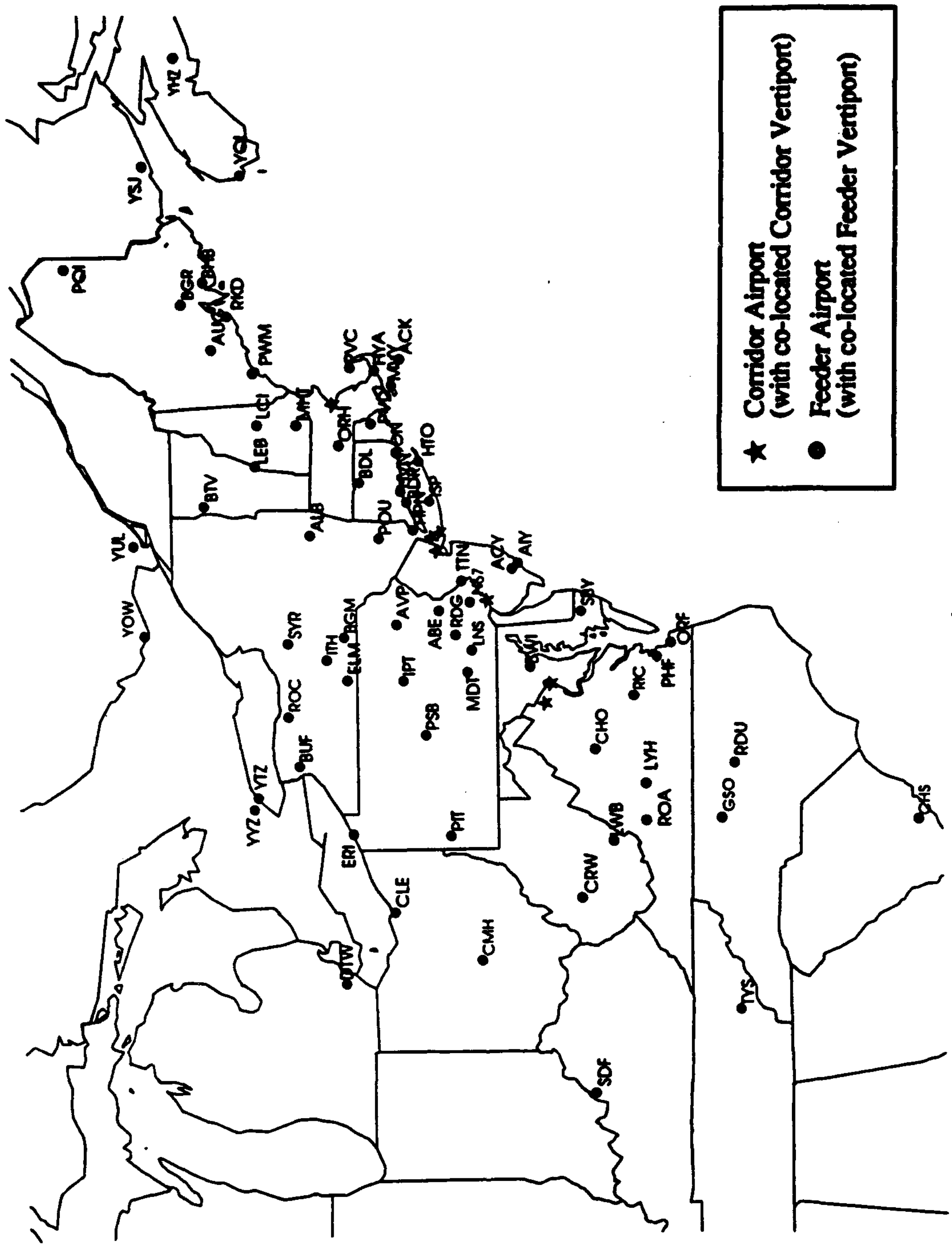


Figure 1-2. Corridor and Feeder Airports and Vertiports

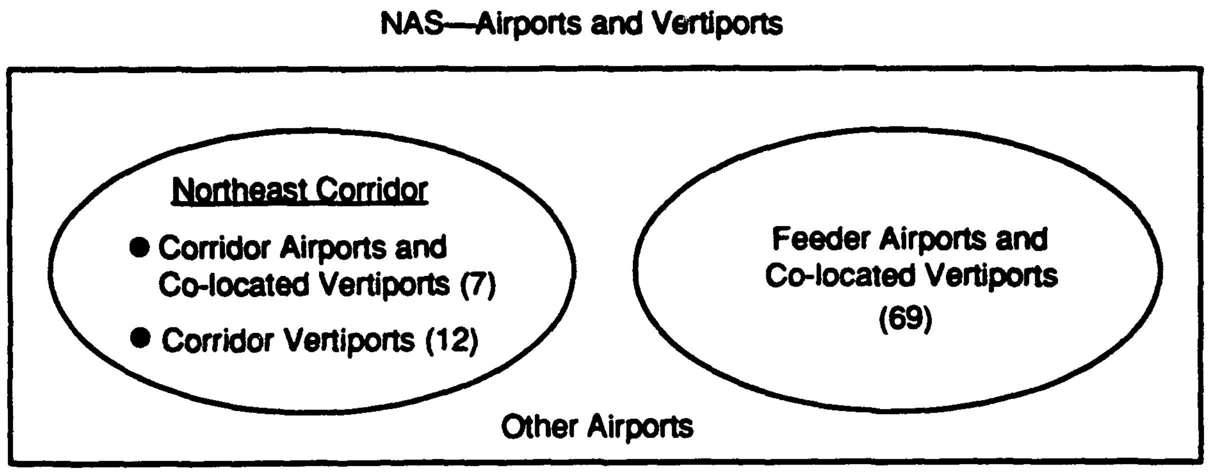


Figure 1-3. Venn Diagram of NAS Airports and Vertiports

1.7 KEY ASSUMPTIONS

All key assumptions made for the *Phase II Delay Analysis* were jointly developed by the Vertical Flight Program Office (VFPO) of the FAA's Research and Development Service, the System Analysis Division of the FAA's Operations Research Service, and CAASD.

There are three major simplifying assumptions in this *Phase II Delay Analysis*:

1. Providing Northeast Corridor CTR service will reduce the demand for Northeast Corridor fixed-wing aircraft service. This reduced demand is modeled by removing the fixed-wing flights identified as candidates for CTR replacement in the *Phase II Market Study*.

2. The capacity or "slots" made available at airports by the reduction in fixed-wing demand would not be refilled. No new fixed-wing demand was assumed to surface in response to the newly available airport capacity. Implicit in this assumption is that airline response (e.g., scheduling additional flights or adjusting schedules of remaining flights) to CTR market capture has not been modeled.

3. CTRs would operate independent of fixed-wing aircraft. CTRs were assumed to operate in an independent vertiport/airspace network and not interact with fixed-wing aircraft on the airport surface or in terminal or en route airspace. In particular, it was assumed that CTRs would not compete with fixed-wing aircraft for the same air traffic control (ATC) resources (e.g., runways, fixes, routes). Implicit in this

assumption is that CTR aircraft are not explicitly modeled and the delays they may incur are not considered.

These are important simplifying assumptions that should be kept in mind when considering the results of this analysis. The results may be very sensitive to these assumptions. The assumptions are admittedly limiting, but they suffice for the intended preliminary nature of the analysis and are acceptable if they are considered in the context of the VFPO's overall work plan for analysis of CTR. Several additional analyses are on-going and planned. Four of them have been designed to explore the sensitivity of the simplifying assumptions made in the *Phase II Delay Analysis* and are described in the following indented paragraphs.

The Volpe National Transportation Systems Center (VNTSC) is undertaking an economic evaluation of the market potential for CTR aircraft. VNTSC's work will provide new estimates of CTR market capture based on a methodology similar to that used in their previous Department of Transportation (DOT) work on high-speed ground transportation. A delay analysis is planned, similar to the *Phase II Delay Analysis* but using the VNTSC results, thus addressing the impact of assumption one.

The FAA Technical Center (FAATC) has recently completed an analysis of the sensitivity of the delay results of the *Phase II Delay Analysis* to demand scenarios that represent a reduced market potential for CTR aircraft. This is equivalent to assuming either a smaller market capture (thus addressing the sensitivity of the delay results to assumption one) or partial refilling of "captured" slots by fixed-wing flights (thus addressing the sensitivity of the delay results to assumption two). The key finding of the sensitivity analysis is that a substantial portion of the *Phase II Delay Analysis* delay savings are realized even if the market capture is assumed to be much smaller, or, equivalently, if a substantial portion of the slots are refilled.

Two studies are currently underway at the FAA and CAASD to assess the effects of CTR aircraft on the terminal and en route airspace environments by explicitly modeling CTR aircraft in terminal and en route airspace. Together, these two studies address assumption three.

The En Route Airspace analysis will examine the simplifying assumption that CTR aircraft would not interact with fixed-wing aircraft in en route airspace. The purpose of the analysis is to assess the effects of Northeast Corridor CTR aircraft service on en route airspace loads. This analysis requires explicitly modeling the tiltrotor aircraft flights that replace the conventional fixed-wing flights that were removed in the *Phase II Delay Analysis*. (Because of differences in aircraft sizes, there is on average a replacement of approximately 1.2 CTR flights for each fixed-wing flight removed.)

The Terminal Airspace analysis will address the simplifying assumption that CTR aircraft would not interact with fixed-wing aircraft in terminal area airspace of the NAS. The purpose of this analysis is to investigate the viability of constructing independent

approach and departure routes for CTR aircraft that do not conflict with the standard approach and departure routes for fixed-wing aircraft.

These additional analyses are described further in section 5 of this report.

1.8 REPORT ORGANIZATION

This report is organized into five sections. The introduction provides the context for the *Phase II Delay Analysis*, including some background information, a statement of purpose, definitions of terms, and a discussion of the key assumptions. Section 2 describes the methodology used in performing the analysis. The analysis results are described in Section 3. Section 4 contains a summary and a discussion of conclusions. Section 5, Next Steps, describes additional analyses of the effects of CTR service on NAS performance. (Results from one of these additional analyses are provided in section 3.4.)

SECTION 2

METHODOLOGY

2.1 OVERVIEW

The *Phase II Delay Analysis* quantifies the maximum delay and cost benefits to the NAS that could be achieved by removing the fixed-wing aircraft flights that are expected to be replaced by the introduction of CTR service in the Northeast Corridor. The methodology, which utilized the NASPAC SMS, consisted of four phases, as illustrated in figure 2-1.

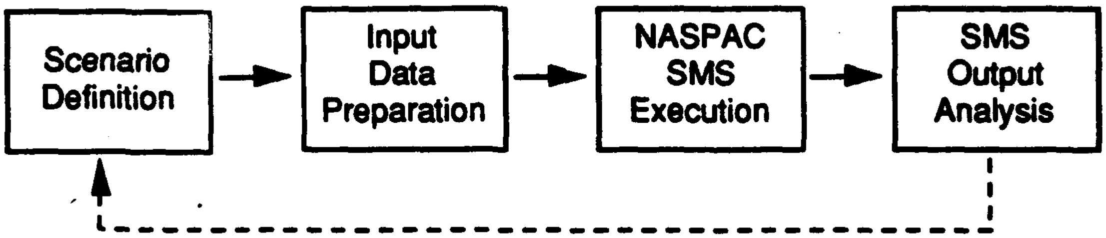


Figure 2-1. An Overview of the *Phase II Delay Analysis* Methodology

2.2 SCENARIO DEFINITION

The two scenarios compared in the analysis consist of a "baseline" scenario, in which only fixed-wing service is available (i.e., no commercial CTR service), and a "removal" scenario, in which it is assumed that both CTR service and fixed-wing service are available. The term "removal" is used to indicate that the fixed-wing flights identified in the *Phase II Market Study* have been removed and assumed to be replaced by CTR flights.

The timeframe for the analysis consists of the years 1990 and 2000. The year 1990 is chosen because it is the timeframe of *Civil Tiltrotor Missions and Applications Phase II: The Commercial Passenger Market* (NASA/FAA, 1991—the *Phase II Market Study*). The *Phase II Delay Analysis* is an elaboration of that study and, as such, investigates the delay implications of the CTR market capture data provided as part of the *Phase II Market Study*. The year 2000 is chosen because it is the target year for the introduction of Northeast Corridor commercial CTR service (according to the *Phase II Market Study*).

The main focus of the *Phase II Delay Analysis* is a comparison of the delay benefits in the year 2000 associated with the removal of fixed-wing aircraft flights expected to be replaced by the introduction of CTR service.

2.3 INPUT DATA PREPARATION

2.3.1 Air Carrier Demand

Table 2-1 summarizes the source of scheduled air carrier demand (for fixed-wing aircraft) data used in the *Phase II Delay Analysis*.

Table 2-1. Air Carrier Demand Data

Year / Scenario	1990	2000
Baseline	February 1990 Official Airline Guide (OAG)	Terminal Area Forecasts (TAF) applied to 1990 baseline OAG
Removal	February 1990 OAG with flights from *Phase II Market Study* removed	TAF applied to 1990 removal OAG

The rows of table 2-1 represent the scenarios studied (baseline and removal), while the columns represent the timeframe (1990 and 2000). For the baseline scenario in the year 1990, scheduled air carrier demand data is taken directly from the February 1990 OAG. For the 1990 removal scenario, the flights identified as candidates for replacement in the *Phase II Market Study* are removed. Appendix B provides a complete listing of the specific fixed-wing flights identified in the *Phase II Market Study* that were removed in order to derive the year 1990 removal scenario.

For the year 2000 scenarios, the NASPAC future demand generator is used to increase the 1990 traffic levels by the growth factors forecast for the year 2000 in the FAA TAF. For the year 2000 baseline scenario, the TAF is applied to the 1990 baseline OAG. For the year

2000 removal scenario, the TAF is applied to the 1990 removal OAG. Additional details regarding the use of the future demand generator can be found in appendix C.

Unscheduled flights are also modeled; they are a feature standard to the NASPAC SMS and are discussed in appendix C.

2.3.2 Airport Capacities

Standard sets of NASPAC estimates for current and future airport capacities are updated where necessary. Sources used to update these estimates of capacity include the FAA Airfield Capacity Model, FAA Engineered Performance Standards (EPS), as well as airport capacity questionnaires completed by tower personnel. All of these sources produce estimates of airfield capacity; these estimates are used to help update the NASPAC data sets as required. For corridor airports, the standard capacities were examined even more thoroughly and adjusted, where appropriate.

For the year 2000, the standard set of NASPAC capacities are updated to reflect procedures and airfield capacity improvements that are included in the 1991–1992 *Aviation System Capacity Plan* and are due to be implemented by 2000.

2.4 NASPAC SMS EXECUTION

The NASPAC SMS execution phase of the *Phase II Delay Analysis* consists of running the SMS to produce results for each of the four scenarios. Table 2-2 describes this phase:

Table 2-2. NASPAC SMS Execution

Scenario \ Year	1990	2000
Baseline	X	X
Removal	X	X

Each "X" in table 2-2 represents a scenario that consists of 18 NASPAC SMS runs. Each set of runs includes 6 runs of different weather days, with 3 replications for each weather day.

These 6 days are the "standard days" used in the NASPAC SMS and were carefully chosen to represent a typical year of weather. Results for the year were estimated by forming a weighted average of the results for the 6 weather days. A list of the 6 days, along with their weighting factors and the distribution of instrument meteorological conditions (IMC) and visual meteorological conditions (VMC) weather at the 7 corridor airports, is included in appendix D. Three replications are executed for each weather day in order to reduce the variation due to the stochastic elements of the NASPAC SMS.

A description of the NASPAC SMS can be found in appendix C.

2.5 NASPAC SMS OUTPUT ANALYSIS

The output analysis focuses on the differences in delays between the baseline and removal scenarios. That difference provides an estimate of the maximum achievable delay benefits associated with the removal of fixed-wing aircraft flights expected to be replaced by the introduction of commercial CTR service in the Northeast Corridor.

The *Phase II Delay Analysis* also includes a cost-of-delays analysis in which the NASPAC SMS Cost of Delays Module (developed by the FAATC and documented in Baart, et al., [1991]) was used to quantify the costs associated with the NASPAC delay results.

SECTION 3

ANALYSIS RESULTS

This section presents the *Phase II Delay Analysis* results. Additional results and output details are provided in appendix D.

3.1 KEY ASSUMPTIONS AND CAVEATS

When interpreting the results of this analysis, the assumptions and caveats discussed in section 1 should be kept in mind. Key among these are the following:

- The scheduled flights that were removed to represent Phase II Demand in the removal scenario were taken from the results of a proprietary Boeing demand model, which were part of the NASA/FAA *Phase II Market Study*.
- It is assumed that there is no refilling of empty slots at airports (slots made available when CTR service operating from vertiports replaces fixed-wing flights).
- Because it is assumed in this analysis that there is no ATC interaction between CTRs and fixed-wing aircraft, the effect of replacing fixed-wing flights with CTRs is modeled by removing those scheduled fixed-wing flights.

As a result of these assumptions, this analysis does not account for:

- Delays for CTR flights (because only fixed-wing flights are modeled explicitly in this analysis)
- Refilling of freed-up airport slots or rescheduling of remaining fixed-wing flights by airlines
- Possible airborne interaction between CTRs and fixed-wing aircraft, which could cause en route delays for fixed-wing aircraft or for CTRs

Either of the possible airline reactions mentioned in the second bullet above, or a failure of CTRs to capture as large a share of the market as implied by the Phase II Demand assumptions, would reduce the number of flights that are replaced by CTRs or at least cause more tightly packed airport schedules (which tend to cause delay). This would likely lead to larger airport delays than those shown in the "removal" scenarios. Summary results of a sensitivity analysis of the Phase II Demand assumptions are provided in section 3.4.

3.2 DEFINITIONS

Two distinct metrics are used to quantify delays when fixed-wing flights are removed. "Technical" delay, also known as operational delay, is incurred by an aircraft while waiting to use an ATC resource. All technical delays reported here are the sum of arrival and departure technical airport delays. "Effective arrival" delay, also known as passenger delay, is the difference between the time an aircraft arrives at its gate in the simulation and its scheduled arrival time. Technical delay is one source of effective arrival delay. All effective arrival delays of scheduled traffic are highly dependent on airline scheduling practices; note that airline reactions to the differences between the baseline and removal scenarios are not modeled. More detailed definitions are provided in appendix D.

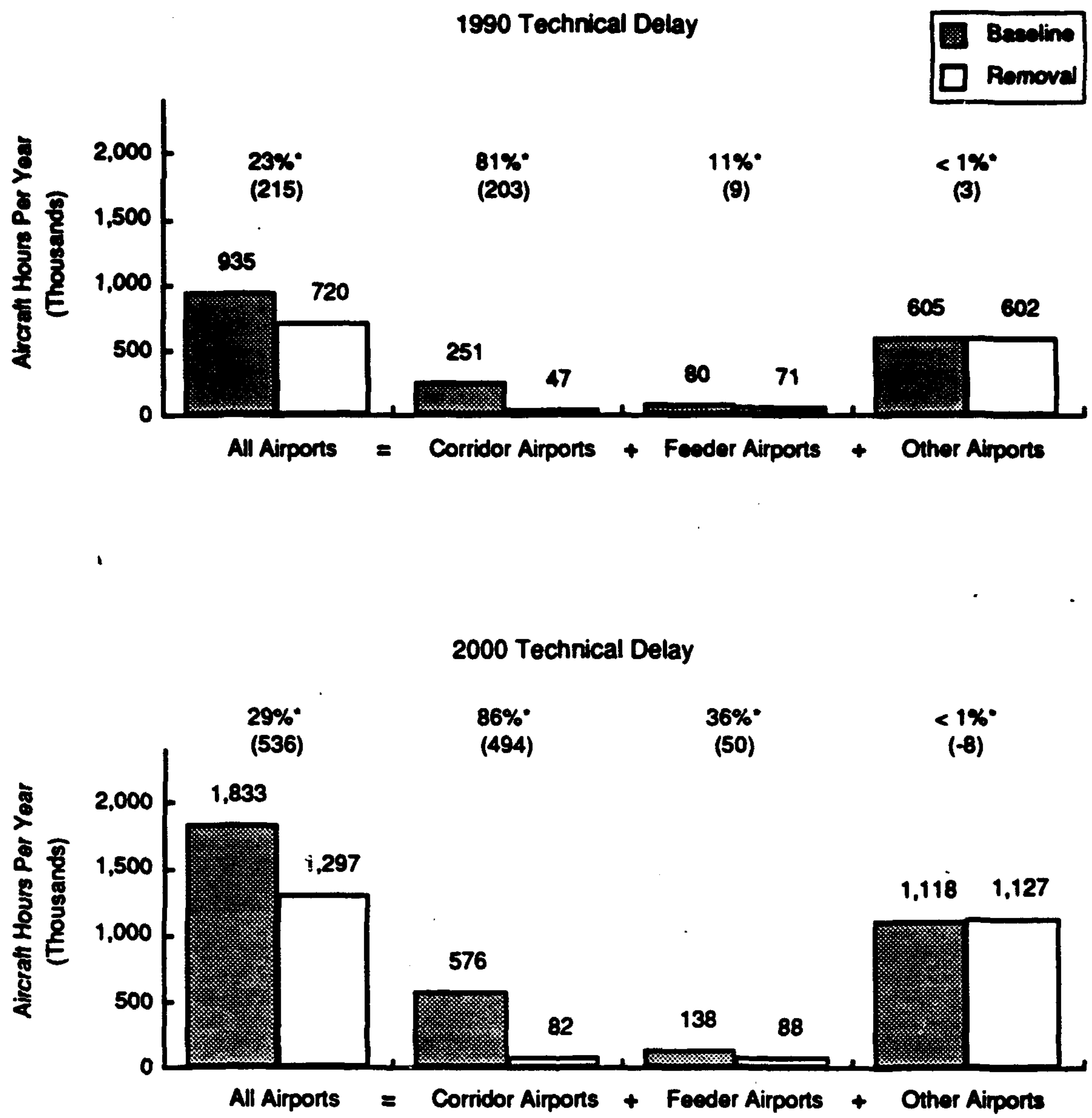
Delay savings are the differences in delays between the baseline and removal scenarios, namely the delay reductions that occur in the removal scenario.

Ripple effects are secondary effects that contribute to effective arrival delay benefits. These delay savings can sometimes occur at airports because of upstream reductions in delay. Ripple effect savings can occur even if there has been no change in the demand pattern, if aircraft have incurred less delay on earlier legs of their itinerary. The effective arrival delay savings due to ripple effect can be sizable in some cases.

There are seven corridor airports and 69 feeder airports. Although some of the feeder airports have a sizable number of flights removed, while others have only a few, all of them are included in the definition of "feeder" airports. Ten of the feeder airports are explicitly modeled as delay-generating, i.e., capacity constrained, airports. The other 59 feeder airports are not considered to be capacity constrained and their technical delay is generally not tracked. Effective arrival delays, however, are tracked at all airports. Note that all instrument flight rules operations in the NAS are explicitly modeled.

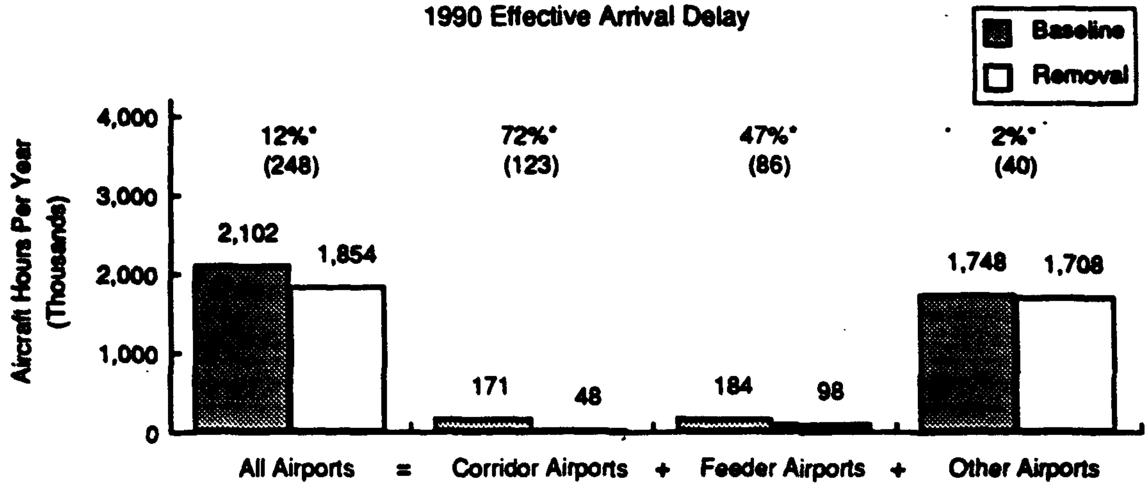
3.3 SYSTEM-WIDE DELAYS

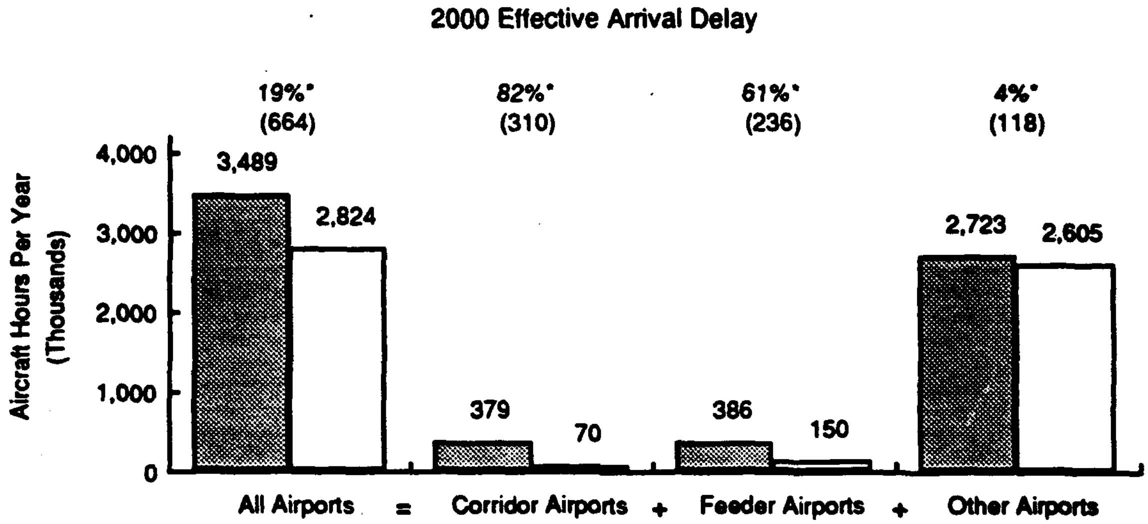
Figures 3-1 and 3-2 summarize the effects on system-wide delays of the introduction of CTR service. Each figure includes bar charts of the results for both the year 1990 and 2000 timeframes. Figure 3-1 displays the technical delay metric and figure 3-2 displays the effective arrival delay metric.



* Estimated annual delay decrease in percent and (in parentheses) aircraft hours per year due to reduction in fixed-wing operations, given *Phase II Delay Analysis* assumptions
Totals do not add exactly because of rounding

Figure 3-1. Technical Delay at All Airports and at Corridor, Feeder, and Other Airports





* Estimated annual delay decrease in percent and (in parentheses) aircraft hours per year due to reduction in fixed-wing operations, given *Phase II Delay Analysis* assumptions
Totals do not add exactly because of rounding

Figure 3-2. Effective Arrival Delay at All Airports and at Corridor, Feeder, and Other Airports

The pairs of bars in each graph show the delay results for the baseline and removal scenarios side-by-side. The first (leftmost) pair of bars in each graph show results for all airports in the NAS. Those results are then divided among the second, third, and fourth pairs of bars, which correspond to corridor airports, feeder airports, and other airports, respectively. The parenthetical numbers above each pair of bars indicate the decreases in delay between the baseline and removal scenarios in thousands of aircraft hours per year. The percentage numbers indicate the percent decreases in delay between the baseline and removal scenarios.

For example, in the upper bar chart of figure 3-1, the results of technical delay are shown for the 1990 timeframe. For this case, the aggregate results for all airports was a total delay of approximately 935,000 aircraft hours for the baseline and 720,000 aircraft hours of technical delay for the removal scenario. Above those two bars, displayed in parentheses, is the savings of 215,000 aircraft hours per year. The savings of 215,000 aircraft hours corresponds to 23 percent of the base value of 935,000 aircraft hours.

To provide a context for evaluating the results, a look at the baseline scenario data is in order. This provides a sense of the magnitude of the expected delays in the absence of any reductions in fixed-wing demand due to the introduction of CTR service. In addition, the large contribution of the seven corridor airports to the total airport delays is demonstrated, underscoring the Northeast Corridor as a logical geographic target for demand reductions. For the baseline scenario, only about 6 percent of all modeled airport operations took place at the seven corridor airports. But, the seven corridor airports' contribution to technical delay in the baseline scenario is about 27 percent in 1990 (251,000 out of 935,000) and 31 percent in 2000 (576,000 out of 1,833,000).

The seven corridor airports' contribution to effective arrival delay in the baseline scenario was only about eight percent in 1990 (171,000 out of 2,102,000) and about eleven percent in 2000 (379,000 out of 3,489,000). The proportion of the effective arrival delay contribution is lower than for the technical delay metric for several reasons, including the fact that technical delays are sizable only where there are capacity problems, but effective arrival delay may be incurred at any airport later in an aircraft's itinerary once the aircraft falls behind schedule. For example, delays which are incurred in the northeast can then "ripple" through the system throughout the day as multi-leg flights continue to other parts of the NAS. In general, effective arrival delay is highly dependent on airline scheduling practices. As an example, for the 47 scheduled flights between Boston Logan and John F. Kennedy International airports in the 1990 baseline scenario, the scheduled gate-to-gate times ranged from 59 to 95 minutes. The gate-to-gate times for six of these 47 flights ranged from 63 to 87 minutes, even though the six flights were scheduled to be flown with the same type of aircraft. Thus, some delay is built into some of the schedules.

Any mechanism for reducing the demand placed on congested airports can be expected to result in dramatic reductions in technical delay at those airports. This is consistent with a queuing theory perspective—the expected waiting time grows exponentially as the level of demand approaches capacity. Because of this highly non-linear relationship, providing some

relief at congested airports in terms of increased capacity or reduced demand can have a dramatic effect on the average airport delays.

The corridor airports accounted for 94 percent of the technical delay savings (203,000 out of 215,000) for 1990 and 92 percent (494,000 out of 536,000) in the year 2000, as shown in figure 3-1. At the feeder airports, the demand reductions were much smaller, on average, than at the corridor airports, and the fraction of technical delay saved was also much less than at corridor airports. As expected, technical delays at "other" airports did not change significantly. Because no flights were removed at "other" airports, any changes in "other" airport technical delays are due to secondary effects.

Figure 3-2 displays the effective arrival delays. They were reduced by 72 percent at the seven corridor airports in 1990 (from 171,000 to 48,000 aircraft hours per year). There was an 82 percent reduction in year 2000 effective arrival delay at the corridor airports. At the feeder airports, there was a 47 percent reduction in effective arrival delay in 1990 when going from the baseline to the removal scenario. In 2000, there was a 61 percent reduction of effective arrival delay. At "other" airports, effective arrival delays were reduced by about two percent in 1990 and by four percent in 2000. Although modest in size, these secondary "ripple effect" savings are nevertheless noticeably larger in 2000, when overall delays are expected to be worse than in 1990.

3.4 SENSITIVITY ANALYSIS

As mentioned in section 1, the FAATC has recently completed an analysis of the sensitivity of the delay results of the *Phase II Delay Analysis* to demand scenarios which represent a reduced market potential for CTR aircraft. The sensitivity analysis estimates the effects on delay savings when replicating the *Phase II Delay Analysis* with lower market capture levels. Fixed-wing demand reductions equal to 25 percent, 50 percent, and 75 percent of the Phase II Demand capture level were examined; aggregate results for the year 2000 are summarized in figure 3-3.

The "Baseline" and "100% of Phase II Demand" (removal) points shown in figure 3-3 are taken from the results of the *Phase II Delay Analysis*. The year 2000 technical delay for "All Airports" is shown in figure 3-1 as 1,833,000 aircraft hours per year for the baseline and 1,297,000 for the removal scenario. These are the two extreme points in the upper chart (operational delay) of figure 3-3. For the year 2000 effective arrival delay, figure 3-3 shows the baseline delay as 3,489,000 and the delay for the removal scenario as 2,824,000 aircraft hours per year, which are the extreme points for the lower chart of figure 3-3 (passenger delay).

The key finding of the sensitivity analysis is that a substantial portion of the Phase II Delay savings are realized even if the market capture rate is assumed to be much lower than the level used in the *Phase II Delay Analysis*. As shown in figure 3-3, between one-half and

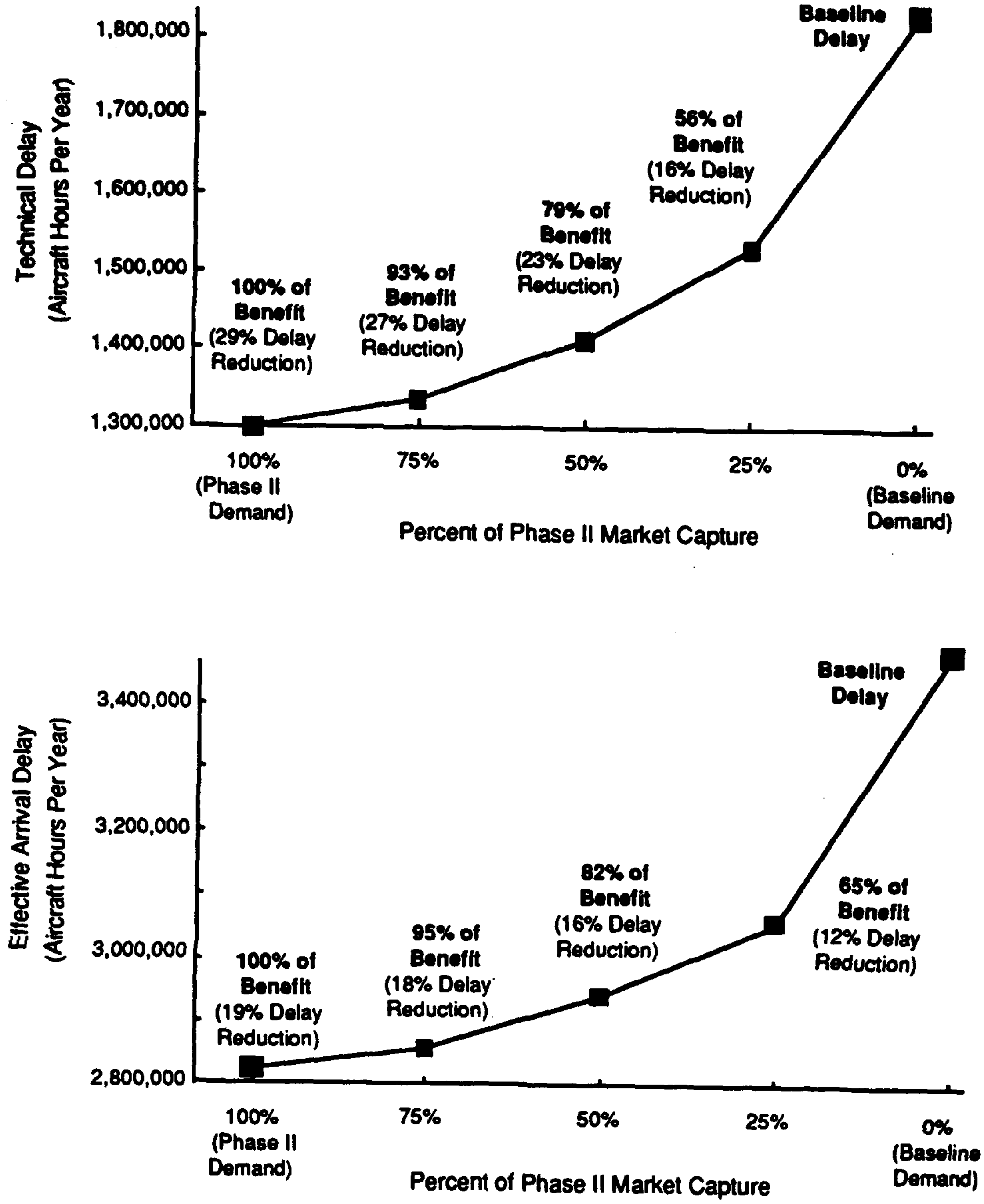


Figure 3-3. Results of Sensitivity Analysis for Year 2000

two-thirds of the delay savings are realized if CTR market capture is reduced to a level of only one-fourth of the level assumed in the *Phase II Delay Analysis*. If the market capture is one-half of that used in the *Phase II Delay Analysis*, delay savings are approximately 80 percent of the delay savings reported in section 3.3. Similar proportional savings are also valid for the cost results reported in section 3.7.

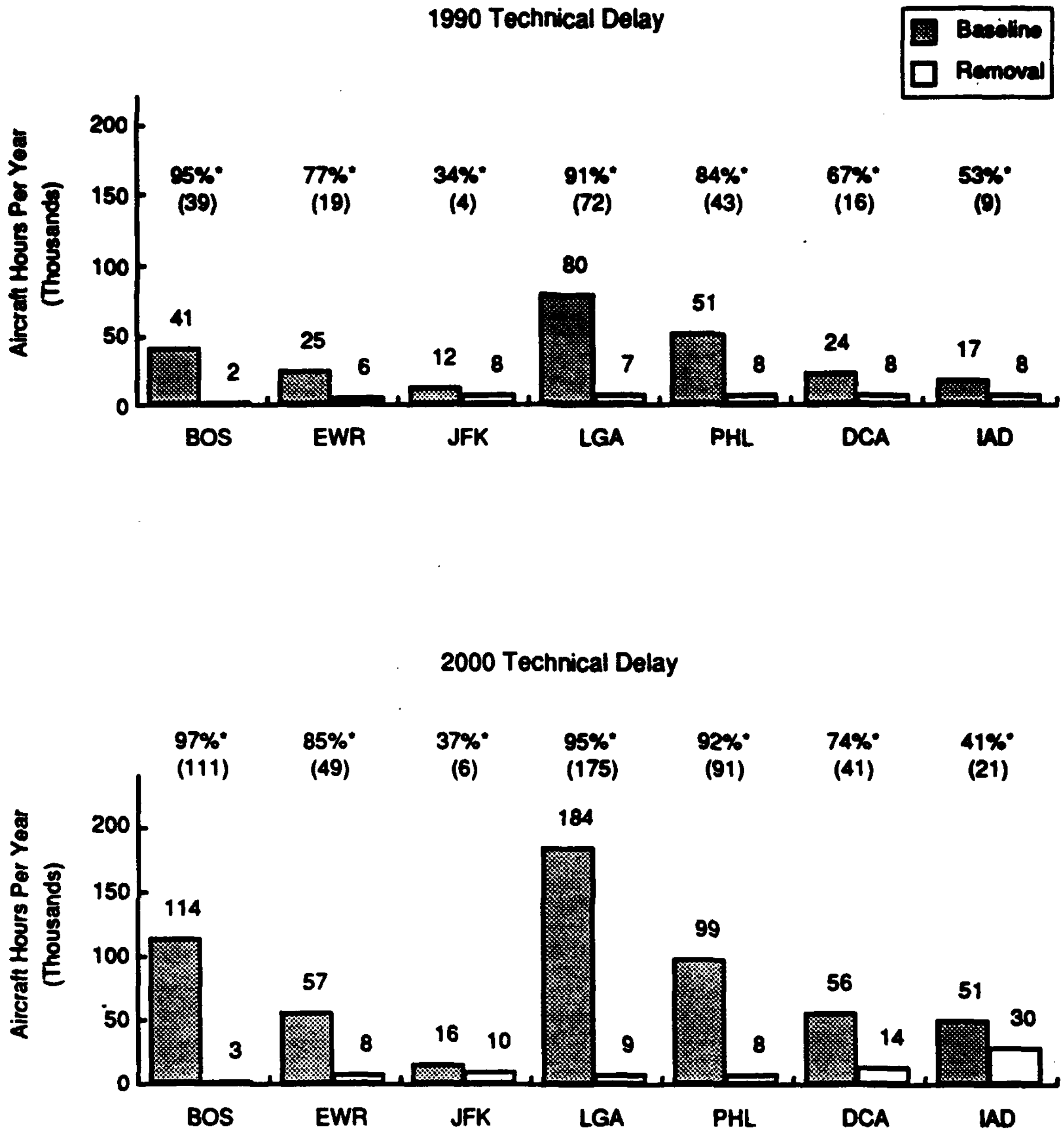
3.5 CORRIDOR AIRPORT DELAYS

For each of the corridor airports, the effects on technical delay and effective arrival delay were measured. Figures 3-4 and 3-5 are bar charts which divide out by individual airport the aggregate results that were presented in figures 3-1 and 3-2 as the "corridor airports" results.

The relationship between these two figures and figures 3-1 and 3-2 can be seen by aggregating the delays shown in figures 3-4 and 3-5. For example, the 1990 technical delay for the baseline scenario shown in the upper chart of figure 3-1 is 251,000 aircraft hours per year. In figure 3-4, the corresponding numbers for the seven corridor airports are 41,000, 25,000, 12,000, 80,000, 51,000, 24,000, and 17,000; the sum of these numbers is 251,000.

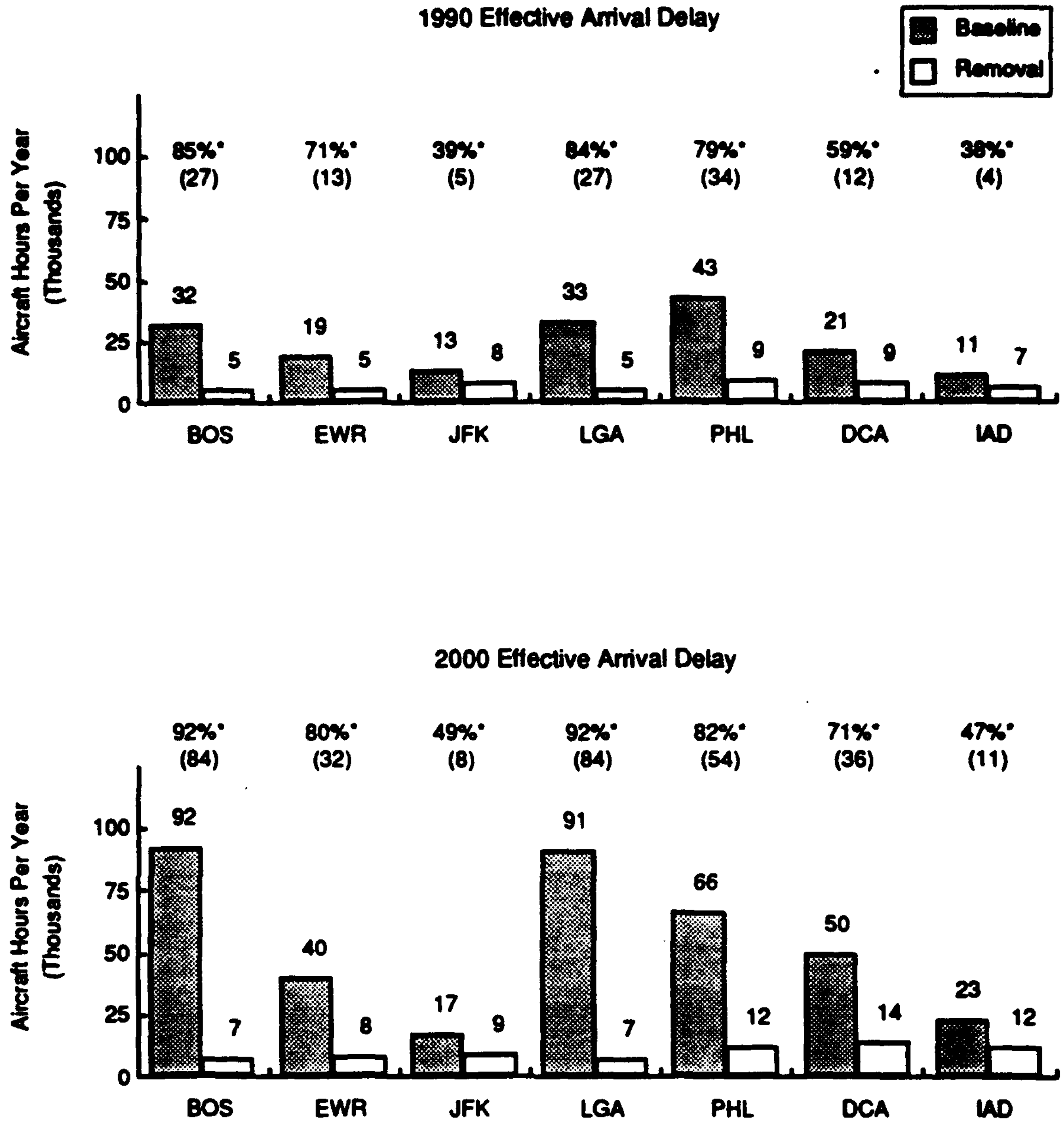
A similar pattern of delay reductions can be seen in each chart. This is because the fraction of delay saved is a function of the fraction of demand removed and of the baseline level of delays. The conclusion is that with only one exception (2000 technical delay at Washington Dulles International), regardless of the value of the baseline delay, the delays at individual airports were reduced to a low number in the removal scenario:

- Year 1990 technical delay is reduced to a level of 2,000 to 8,000 hours.
- Year 2000 technical delay is reduced to a level of 3,000 to 14,000 hours.
- Year 1990 effective arrival delay is reduced to a level of 5,000 to 9,000 hours.
- Year 2000 effective arrival delay is reduced to a level of 7,000 to 14,000 hours.



* Estimated annual delay decrease in percent and (in parentheses) aircraft hours per year due to reduction in fixed-wing operations, given *Phase II Delay Analysis* assumptions

Figure 3-4. Technical Delay at Individual Corridor Airports



* **Estimated annual delay decrease in percent and (in parentheses) aircraft hours per year due to reduction in fixed-wing operations, given *Phase II Delay Analysis* assumptions**

Figure 3-5. Effective Arrival Delay at Individual Corridor Airports

The only exception to these patterns occurred with technical delay at Washington Dulles International in the year 2000. In that situation, off-the-runway restrictions in the Washington area prevented technical departure delay from being reduced as much as elsewhere; consequently, a smaller savings was achieved. Note also that the second largest technical delay in the year 2000 removal scenario was Washington National (with 14,000 hours), which was subject to similar off-the-runway departure restrictions.

Although 14,000 aircraft hours per year is not an insignificant number, it is small in comparison to the baseline delay values and on a per-flight basis. On a per-flight basis, for example, the largest 1990 technical delays in the removal scenario are 3 minutes per departure at Washington Dulles International and 2 minutes per arrival at John F. Kennedy International. In the 2000 removal scenario, the largest average technical delays per flight are 8 minutes per departure at Washington Dulles International and 3 minutes per arrival at John F. Kennedy International.

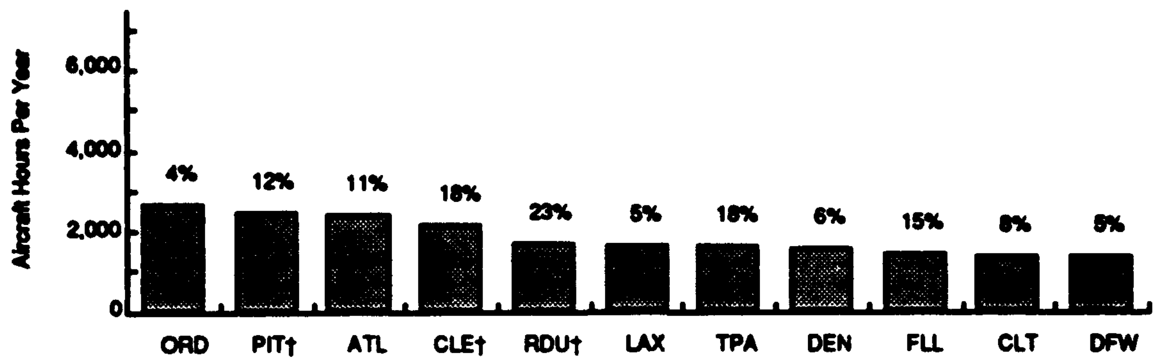
3.6 OTHER RIPPLE EFFECT BENEFITS

As was clear from figure 3-2, the introduction of CTR service in the northeast resulted in a small but significant net reduction in effective arrival delays at other airports (where no flights were removed). Figure 3-6 shows the airports with the greatest savings in effective arrival delay when comparing the baseline scenarios to the removal scenarios. These benefits were largest, in terms of total aircraft hours per year, at busy airports that have many scheduled flights connecting to the corridor airports (e.g., Chicago O'Hare and Atlanta Hartsfield).

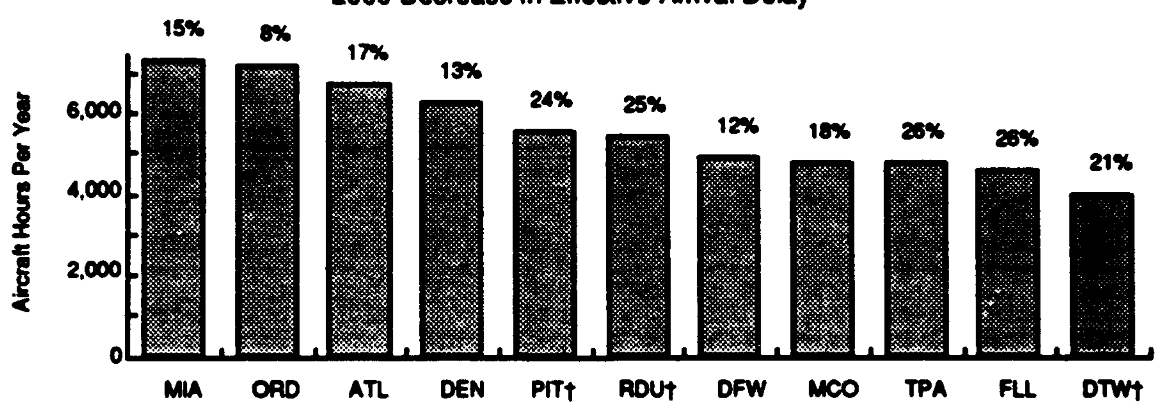
When interpreting the results of these graphs, the reader should bear in mind that the magnitude of the total benefits to these other airports is more robust than the distribution of these benefits among particular airports. If itineraries change, the particular airports that benefit the most would be expected to change, but the overall effects would still occur somewhere. For example, this analysis was based on scheduled demand data for an individual day in February; had a summer day been used, the itineraries would likely have been different, resulting in a different distribution among airports.

Appendix D includes the airport-specific results in tabular form. A review of those results shows a few instances of negative impact on both technical and effective arrival delay. However, those numbers are fairly small, and the impact is minimal compared with instances of delay savings. Again, aggregate results are generally more robust than results for individual airports.

Maximum Achievable CTR Benefits
Based on Phase II Delay Scenario:
1990 Decrease in Effective Arrival Delay *



Maximum Achievable CTR Benefits
Based on Phase II Delay Scenario:
2000 Decrease in Effective Arrival Delay *



* Estimated annual delay decrease in aircraft hours per year (and in percent above bars) due to reduction in fixed-wing operations, given *Phase II Delay Analysis* assumptions

† Small-market-capture (< 3%) feeder airport

Figure 3-6. Ripple-Effect Benefits (Effective Arrival Delay)

3.7 AGGREGATE COST OF DELAYS

The "Cost of Delays" module, developed by the FAATC (documented in [Baart, et al., 1991]), was used to compute the costs associated with the aggregate delay results which are included in section 3.3. This section summarizes these costs, which are calculated only for the "All Airports" category, i.e., system-wide from an airports' perspective. Table 3-1 summarizes the cost savings for the two timeframes considered in this analysis and for the two delay metrics used elsewhere in this document. (Operational delay is another term for technical delay, and passenger delay is another term for effective arrival delay.)

Aircraft costs were applied to the technical delays to construct the "Operational Delay" costs. These costs are based on the sum of estimated airborne and ground holding costs for aircraft. These are costs borne by all aircraft for additional time spent in airborne or ground delays. It is not intended to include all costs of delays in the system. For example, airlines incur additional expenses that are not captured here, such as aircraft carrying contingency fuel to avoid a diversion "just in case" there is an arrival airborne hold. Passenger costs were calculated based on the estimated costs of delay for passengers arriving later than their scheduled arrival time (no cost reduction is given here to early arrivals), based on effective arrival delays.

Table 3-1. Cost of Delay Savings
($1,000,000s)

Delay Cost Type	1990	2000
Operational Delay	$300	$ 700
Passenger Delay	$300	$1,000

Operational and passenger costs for both timeframes are based on 1992 dollars. The larger cost savings for the year 2000 are thus solely the result of greater delay savings and not because of a different measurement approach. Although military and general aviation aircraft together account for a sizable portion of delay when measured in *aircraft hours*, air carrier delays dominate the results when measured in terms of operational and passenger *costs*. (For example, in the 1990 baseline scenario, less than 79% of the technical delay hours were incurred by air carrier flights, but in dollar terms they amounted to over 93% of the total.)

The fraction of cost savings due to the reduction in fixed-wing demand expected from the introduction of CTR service is consistent with the system-wide delay savings as summarized

in section 3.3. The $300 million in 1990 operational delay cost savings is out of a baseline cost of $1,200 million. This 25 percent savings is comparable to the 23 percent savings shown in figure 3-1. Similarly, the $700 million in operational costs saved in year 2000 out of a $2,100 million baseline is close to the 29 percent delay benefit shown in figure 3-1. For passenger delay costs, the $300 million savings comes from a baseline of $2,200 million and the $1,000 million savings in year 2000 comes from a baseline of $4,200 million. These cost savings proportions are similar to the delay savings shown in figure 3-2 of 12 percent in 1990 and 19 percent in 2000.

The magnitude of these savings clearly demonstrates that a significant portion of the NAS's delays are concentrated in the Northeast Corridor and that, given the assumptions of this analysis, a sizable portion of those technical delay costs can potentially be saved by implementing CTR service. Because Northeast Corridor airports have a greater share of traffic that includes large, expensive aircraft (such as air carrier aircraft), delays at these seven airports are more costly than the NAS average. The fraction of savings when measured in dollars is slightly higher than when measured in aircraft hours because much of the cost savings are concentrated in the Northeast Corridor.

SECTION 4

DISCUSSION AND CONCLUSIONS

This section highlights some of the results presented in the previous section in the context of the three key assumptions of the *Phase II Delay Analysis*. It is important to remember that the *Phase II Delay Analysis* results represent an upper bound on delay benefits associated with introducing CTR service in the Northeast Corridor.

At a very high level and given the assumptions described herein, the *Phase II Delay Analysis* demonstrates that the hypothesized reduction of fixed wing demand due to the introduction of civil tiltrotor service in the NAS will reduce airport delays. Not surprisingly, the largest delay reductions tended to occur at congested airports that had large numbers of flights removed. For example, the three corridor airports that showed the largest delay reductions were also the three corridor airports that had the greatest percentage of their scheduled air carrier flights removed in the modeled removal scenario (i.e., Boston Logan with 52% CTR market capture; La Guardia with 38% CTR market capture; and Philadelphia with 35% CTR market capture.) Nevertheless, ripple-effect delay reductions did occur at major airports outside the Northeast Corridor, such as Chicago O'Hare, Atlanta Hartsfield, Denver, Los Angeles, Dallas-Fort Worth, and Miami, where no flights were removed.

Again, these conclusions must always be qualified in terms of the key assumptions; the results of this analysis may be very sensitive to those assumptions. This sensitivity will be explored further in analyses that are on-going and planned (see section 5). The Phase II Demand scenario, taken from the *Phase II Market Study*, assumes large demand reductions within the markets considered (described in detail in appendix B); fifty-eight percent of scheduled corridor flights and 75% of scheduled feeder flights were identified as candidates for CTR replacement. Accordingly, these flights were removed in this *Phase II Delay Analysis* removal scenario. For example, within the corridor market, 22 out of 22 scheduled flights were removed (or assumed "captured" by CTR service) between Washington National and Newark International; in the feeder market, 31 out of 31 scheduled flights were removed between Boston Logan and Islip. Based on passenger demand assumptions in the *Phase II Market Study*, considerably lower market capture is assumed for some airport pairs as shown in detail in appendix B.

The following subsections provide an overview of the technical and effective arrival delay reductions associated with reductions in fixed-wing demand brought on by the introduction of CTR service in the Northeast Corridor. These are maximum achievable delay benefits associated with the *Phase II Delay Analysis* assumptions.

4.1 TECHNICAL DELAY REDUCTIONS

The maximum achievable delay benefits due to CTR service in terms of **technical delay** (for a definition of technical delay, see section 3.2) are summarized in table 4-1. The percent delay reduction columns (one for year-1990 results and one for year-2000 results) show the difference between the baseline scenario delay results and the removal scenario delay results, divided by the baseline scenario delay results. The third column provides a context or framework in which to interpret these delay reduction results by indicating the percent of the total number of scheduled and unscheduled flights removed in each airport category; note that only scheduled flights were actually removed. There is a strong relationship between airport demand and airport delay, with the largest technical delay reductions occurring at the corridor airports, where the largest demand reductions occur. Similarly, moderate technical delay reductions occur at the feeder airports where moderate demand reductions occur, and negligible technical delay reductions occur at all other airports (airports other than the corridor and feeder airports, figure 1-2) where no flights are removed. Most notable, perhaps, is the "bottom line" or bottom row of table 4-1, where it is shown that, given *Phase II Delay Analysis* assumptions, reducing fixed-wing demand through the introduction of CTR service in the Northeast Corridor could reduce nationwide airport technical delay by about one fourth.

Table 4-1. Summary of Percent Technical Delay Reductions

Airport Category	Technical Delay Reductions in 1990	Technical Delay Reductions in 2000	*Percent of All Flights Removed*
Corridor Airports	81%	86%	*29%*
Feeder Airports	11%	36%	*10%*
Other Airports	<1%	<1%	*0%*
All Airports	23%	29%	*3%*

The three corridor airports with the largest delay reductions in aircraft-hours per year were La Guardia, Philadelphia International, and Boston Logan (in that order) in 1990; and the same three, La Guardia, Boston Logan, and Philadelphia International (in that order) in 2000. While it is assumed that La Guardia and Boston Logan will receive no capacity improvements by the year 2000, it is assumed that Philadelphia International will build a new

parallel commuter runway, 3/26, by the year 2000, thus increasing its airport capacity and reducing airport delay.

The three feeder airports with the largest delay reductions in aircraft-hours per year were Baltimore-Washington International, White Plains, and Bradley in 1990, and Bradley, White Plains, and Islip in 2000. It is assumed that Baltimore-Washington International will build a new parallel runway, 10R/28L, by the year 2000, thus increasing its airport capacity. A 68% increase in demand by the year 2000 is forecast at Bradley according to the Terminal Area Forecast from April 1990, perhaps contributing to a large potential for delay reduction in year 2000.

As shown in the third row of table 4-1, negligible technical delay effects were found at airports outside the corridor and feeder airports. As illustrated in figure 4-1, technical delay benefits stay within the corridor and feeder network. The airports shown in figure 4-1 are, in terms of technical delay, the 10 airports experiencing the largest delay reductions in the Northeast Corridor in either the year 1990 or the year 2000, or both; a total of 13 airports.

As mentioned above, it is important to note the last row of table 4-1; the Northeast Corridor and its feeders can potentially have such a large effect on the system, given *Phase II Delay Analysis* assumptions, as to reduce system-wide airport technical delays by about one fourth.

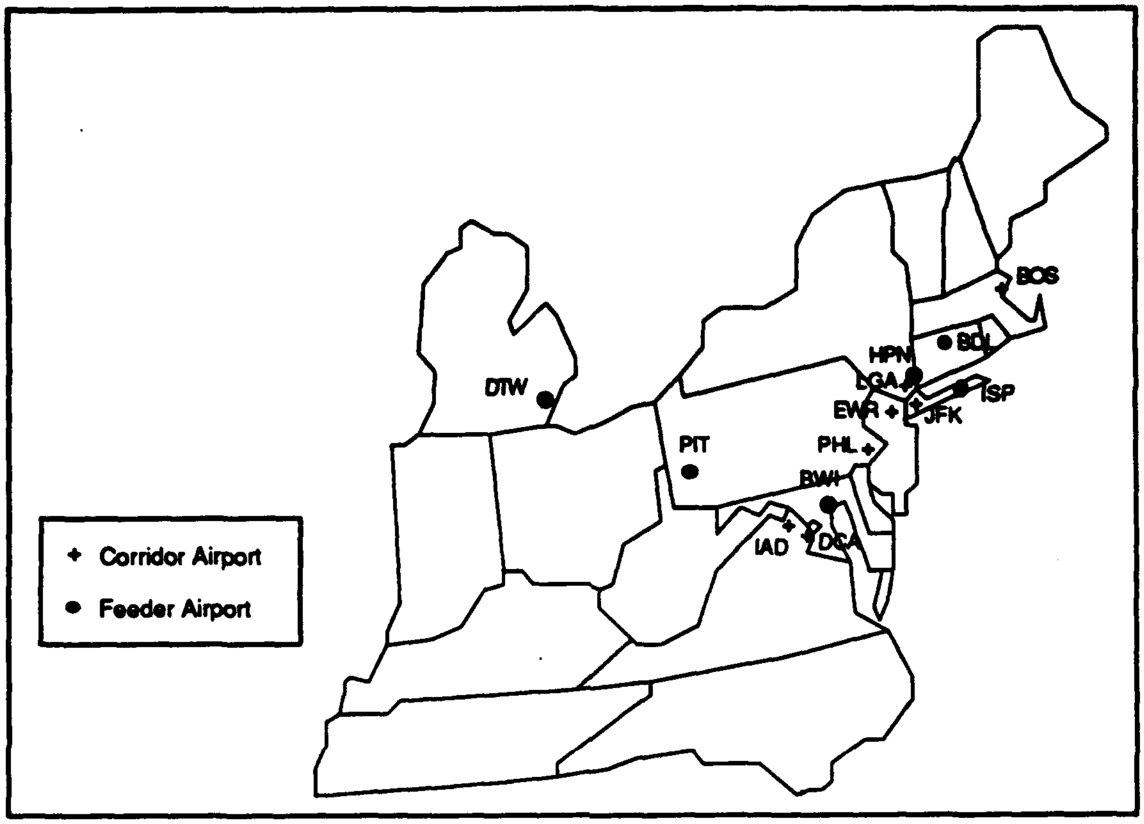


Figure 4-1. Airports with Largest Technical Delay Reductions

4.2 EFFECTIVE ARRIVAL DELAY REDUCTIONS

The maximum achievable delay benefits in terms of **effective arrival delay** (for a definition of effective arrival delay, see section 3.2), which includes "ripple-effect" delay, are summarized in table 4-2. As in table 4-1, results are presented for 1990 and 2000, along with the percentage of all flights removed in each category. The strong relationship between airport demand and airport delay is noticeable, as the largest effective arrival delay reductions occur at the corridor airports, where the largest demand reductions occur. Similarly, moderate effective arrival delay reductions occur at the feeder airports where moderate demand reductions occur. Most notable is that effective arrival delay reductions occur at other airports (third row table 4-2) **outside** the corridor and feeder network where **no** flights are removed.

Table 4-2. Summary of Percent Effective Arrival Delay Reductions

Airport Category	Effective Arrival Delay Reductions in 1990	Effective Arrival Delay Reductions in 2000	*Percent of All Flights Removed*
Corridor Airports	72%	82%	*29%*
Feeder Airports	47%	61%	*10%*
Other Airports	2%	4%	*0%*
All Airports	12%	19%	*3%*

The three corridor airports with the largest delay reductions in aircraft hours per year were Philadelphia International, La Guardia, and Boston Logan (in that order) in 1990; and the same three, Boston Logan, La Guardia, and Philadelphia International (in that order) in 2000. While it is assumed that La Guardia and Boston Logan will receive no capacity improvements by the year 2000, it is assumed that Philadelphia International will build a new parallel commuter runway, 3/26, by the year 2000, thus increasing its airport capacity.

The three feeder airports with the largest delay reductions in aircraft-hours per year were Baltimore-Washington International, Bradley, and White Plains in 1990, and Bradley, White Plains, and Islip in 2000. It is assumed that Baltimore-Washington International will build a new parallel runway, 10R/28L, by the year 2000, thus increasing its airport capacity. A 68% increase in demand by the year 2000 is forecast at Bradley according to the Terminal Area Forecast from April 1990, perhaps contributing to a large potential for delay reduction in year 2000.

The three "other" airports outside the corridor and feeder network with the largest delay reductions in airport-hours per year were Chicago O'Hare, Atlanta Hartsfield, and Los Angeles International in 1990, and Miami International, Chicago O'Hare, and Atlanta Hartsfield in 2000. It is assumed that Atlanta Hartsfield International will build a fifth parallel runway, 9R/27L, by the year 2000, thus increasing its airport capacity. A 21% increase in demand by the year 2000 is forecast at Miami International according to the Terminal Area Forecast from April 1990, perhaps contributing to a large potential for delay reduction in year 2000. As illustrated in figure 4-2, the airports with the largest effective arrival delay benefits are not just within the corridor and feeder network. Ripple-effect delay benefits are found at several major airports across the country. These include a cluster of airports in Florida (Orlando, Tampa, Fort Lauderdale and Miami). This effect can be

partially explained by noting the strong relationship between the Northeast Corridor and Florida, especially in February, the timeframe of the OAG used in this analysis. The 24 airports shown in figure 4-2 are, in terms of effective arrival delay, those airports receiving a delay reduction of greater than 1,500 aircraft hours in the year 1990, and those airports receiving a delay reduction of greater than 4,500 aircraft hours in the year 2000.

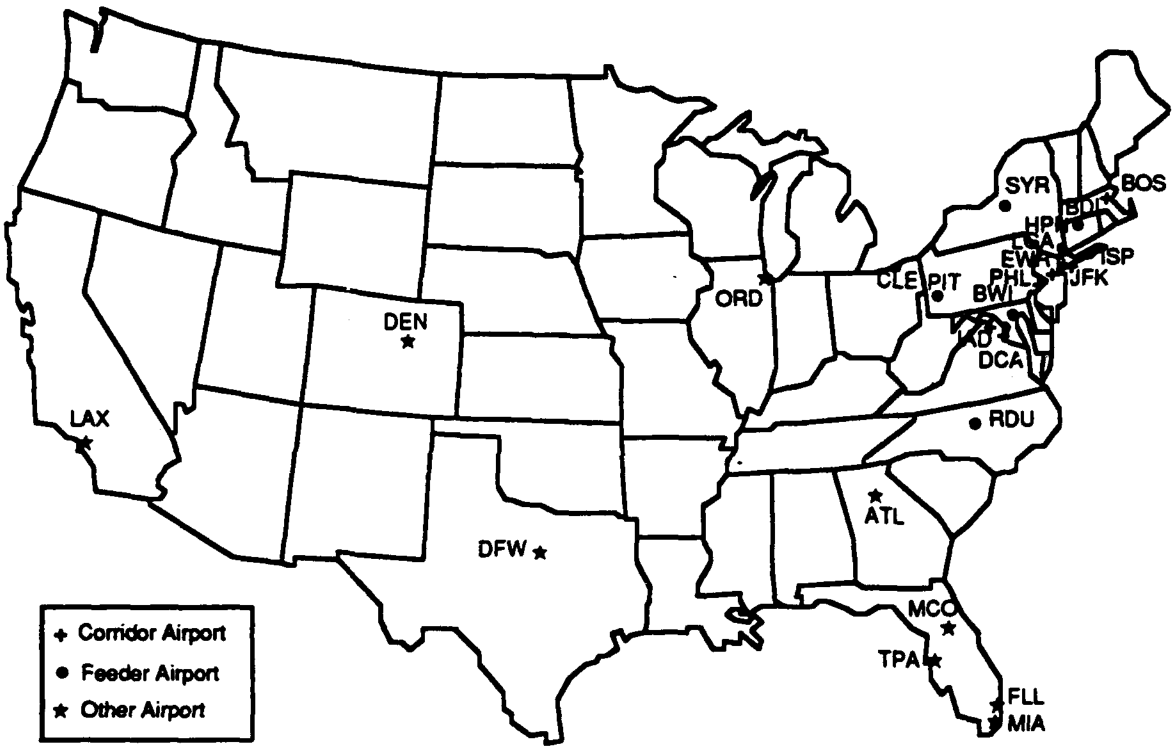


Figure 4-2. Airports With Largest Effective Arrival Delay Reductions

4.3 COMPARISON OF CTR DELAY SAVINGS WITH DELAY SAVINGS FROM OTHER HYPOTHETICAL SYSTEM IMPROVEMENTS

This section has been included to provide context for the *Phase II Delay Analysis* results. Please note that the purpose of this information is only to provide context and NOT to provide a comparison of viable alternatives.

In order to provide some context in which to interpret the magnitude of the delay savings presented elsewhere in this document, a separate set of year 2000 simulation runs were made. These runs included representations of hypothetical system capacity improvements. The hypothetical system improvements chosen for this comparison are two new independent parallel runways–one each at Boston Logan and La Guardia airports. In particular, Boston Logan and La Guardia airports were selected for this comparison because they received the largest delay reductions in the *Phase II Delay Analysis*. Although it would be extremely difficult to construct new independent parallel runways at either airport and there are no plans to do so, these improvements would provide a great relief to the northeast ATC system. As such, these hypothetical system improvements are intended to provide a benchmark against which to compare the *Phase II Delay Analysis* results. Table 4-3 shows the results of the comparison.

Table 4-3. Comparison of Year 2000 CTR Delay Savings
With Delay Savings From Hypothetical System Improvements

Delay Metric	CTR Phase II Delay		Hypothetical System Improvements	
	Percent	Absolute	Percent	Absolute
Technical Delay	29%	540,000	14%	250,000
Effective Arrival Delay	19%	660,000	9%	320,000

The comparison demonstrates that, given the assumptions of the *Phase II Delay Analysis*, the delay savings associated with introducing CTR service would be roughly twice as great as the delay savings associated with the construction of the hypothetical new runways at Boston Logan and La Guardia. As with all results included in this report, it is important to interpret them within the context of the *Phase II Delay Analysis* assumptions and to remember that the *Phase II Delay Analysis* delay savings are an upper bound on delay benefits associated with introducing CTR service in the Northeast Corridor.

SECTION 5

NEXT STEPS

As stated in section 1, the *Phase II Delay Analysis* is not intended to stand alone. Rather, it should be considered as one in a series of analyses. Sections 5.1 through 5.4 briefly describe four analyses specifically designed to address the three key limiting assumptions made in this analysis. Section 5.5 lists some of the other ongoing work and section 5.6 lists potential future analyses related to CTR.

5.1 ECONOMIC EVALUATION OF CTR MARKET POTENTIAL

A key assumption made in the *Phase II Delay Analysis* relates to the level of fixed-wing aircraft demand that was assumed to be captured by CTR service. The VNTSC is undertaking an economic evaluation of the market potential for CTR aircraft in the United States and of potential societal benefits from CTR service. Their inter-modal diversion model captures both the increase in CTR demand and the corresponding decrease in fixed-wing demand. VNTSC's work will provide estimates of CTR market capture based on a methodology similar to that used in their previous DOT work on high-speed ground transportation. This will provide an updated demand scenario which is consistent with other DOT analyses. The *Phase II Delay Analysis* estimates delay savings based on the *Phase II Market Study*. A follow-on delay analysis, similar to the *Phase II Delay Analysis* but using the VNTSC results, is planned, thus addressing the impact of Assumption 1 in section 1.7.

5.2 SENSITIVITY ANALYSIS

The Phase II Demand scenario, taken from the *Phase II Market Study*, assumes large demand reductions within the markets considered (described in detail in appendix B); 58% of scheduled corridor flights and 75% of scheduled feeder flights were identified as candidates for CTR replacement. Accordingly, these flights were removed in this *Phase II Delay Analysis* removal scenario.

The recently completed sensitivity analysis assessed the sensitivity of the *Phase II Delay Analysis* results to reduced market capture. It was conducted by the FAATC based on the experimental design and data provided from the *Phase II Delay Analysis*. Summary findings of the sensitivity analysis are included in section 3.4 of this report.

As shown in figure 5-1 (which has no scale and is representing neither specific airports nor specific aggregate numbers), delay is dependent on the aggregate level of demand. The *Phase II Delay Analysis* has identified two points on this abstract curve—0% market capture and Phase II Demand market capture (as defined in the *Phase II Market Study*). The

sensitivity analysis determined three more points on the curve: 25%, 50%, and 75% of the Phase II Demand market capture.

This reduced market capture analysis can be thought of in two ways: as an airline response to Phase II Demand market capture (e.g., refilling of slots made available by the reduction in fixed-wing demand associated with introducing CTR service), or as a less-optimistic outcome of the introduction of CTR service than assumed in the Phase II Demand scenario of the *Phase II Market Study*. Because the *Phase II Delay Analysis* assumption of no interaction between conventional and CTR aircraft was retained for the sensitivity analysis, the two ways of describing it are equivalently modeled. In either case, the sensitivity analysis assessed the sensitivity of the *Phase II Delay Analysis* results to reduced market capture and addressed the impact of Assumptions 1 and 2 in section 1.7.

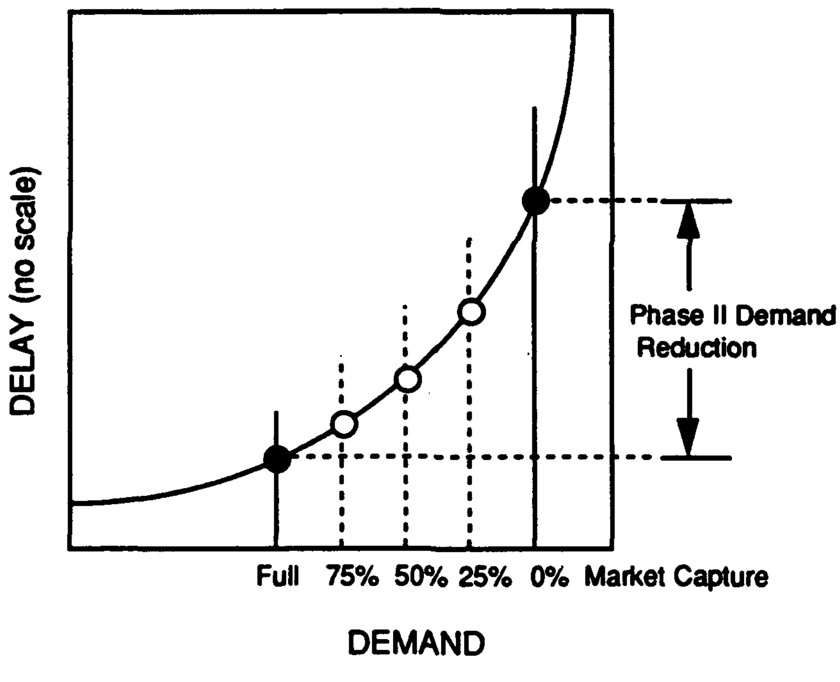


Figure 5-1. Relationship Between Demand and Delay

5.3 EN ROUTE AIRSPACE ANALYSIS

The En Route Airspace Analysis will examine the simplifying assumption that CTR aircraft would not interact with fixed-wing aircraft in en route airspace of the NAS. The purpose of this analysis is to assess the effects of Northeast Corridor CTR service on en route airspace loads. This analysis requires explicit modeling of the CTR flights that replace the conventional flights that were removed in the *Phase II Delay Analysis*. (Because of differences in aircraft sizes, there is on average a replacement of 0.8 CTRs for each fixed-wing aircraft for feeder flights and 3.5 CTRs for each fixed-wing aircraft for Corridor flights.) The CTR replacement flights will be assigned routes and modeled explicitly in the en route airspace using the NASPAC SMS. Year 1990 and year 2000 baseline and replacement scenarios, with a conservative assumption regarding weather conditions, will be analyzed.

5.4 TERMINAL AREA AIRSPACE STUDY

The Terminal Airspace analysis will address the simplifying assumption that CTR aircraft would not interact with fixed-wing aircraft in terminal area airspace of the NAS. The purpose of this analysis is to investigate the viability of constructing independent approach and departure routes for CTR aircraft that do not conflict with the standard approach and departure routes for fixed-wing aircraft. The New York to Boston corridor has been chosen for demonstrating proof-of-concept CTR terminal airspace routes. This analysis is being performed in coordination with FAA headquarters and field personnel.

5.5 OTHER CTR-RELATED ACTIVITIES

In addition to the four analyses described above, the VFPO of the FAA's Research and Development Service is involved in a number of other ongoing CTR-related activities:

- Terminal Instrument Procedures (TERPS) development for CTR
- Implementation of a noise research and development plan addressing key CTR noise requirements and projects
- Development of planning guidelines for vertiports/large heliports that will handle tiltrotor aircraft and other large rotorcraft

5.6 POSSIBLE FUTURE ANALYSES

The following paragraphs provide ideas for possible future analyses that go beyond the scope of the analyses that are on-going and planned.

Other tools or models could potentially be applied for more detailed localized analysis of CTR service in the Northeast Corridor. For example, an airspace analysis of interactions of CTR and fixed-wing aircraft in the terminal area could be accomplished, using another existing model such as SIMMOD (Airport and Airspace Simulation Model). This type of more localized terminal airspace analysis that evaluates the feasibility of approaches and departures into and out of a major metropolitan area may need to be considered.

The effects of the introduction of CTR service in other major geographical areas of the NAS may be another area for future analysis. The *Phase II Market Study* highlights several other potential markets in the continental United States such as a California corridor; a central United States corridor including Chicago, Memphis, Louisville, and perhaps Pittsburgh; and a Texas corridor including Dallas and Houston.

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APPENDIX A

CORRIDOR AND FEEDER AIRPORTS

The following table provides the location identifier (LocID), airport name, city, and state of all the corridor and feeder airports addressed in this analysis.

Table A-1. Corridor and Feeder Airports

Corridor Airports

LocID	Airport Name	City, State
BOS	Boston Logan International Airport	Boston, MA
DCA	Washington National Airport	Washington, DC
EWR	Newark International Airport	Newark, NJ
IAD	Washington Dulles International Airport	Washington, DC
JFK	John F. Kennedy International Airport	New York, NY
LGA	New York La Guardia Airport	New York, NY
PHL	Philadelphia International Airport	Philadelphia, PA

Feeder Airports

LocID	Airport Name	City, State
ABE	Allentown-Bethlehem-Easton Airport	Allentown, PA
ACK	Nantucket Memorial Airport	Nantucket, MA
ACY	Atlantic City International Airport	Atlantic City, NJ
AIY	Atlantic City Municipal/Bader Field Airport	Atlantic City, NJ
ALB	Albany County Airport	Albany, NY
AUG	Augusta State Airport	Augusta, ME
AVP	Wilkes-Barre/Scranton International Airport	Wilkes-Barre/ Scranton, PA
BBX/N67	Philadelphia Wings Field Airport	Philadelphia, PA
BDL*	Windsor Locks Bradley International Airport	Windsor Locks, CT
BDR	Bridgeport Igor I. Sikorsky Memorial Airport	Bridgeport, CT
BGM	Binghamton Edwin A. Link Field-Broome County Airport	Binghamton, NY
BGR	Bangor International Airport	Bangor, ME
BHB	Hancock County-Bar Harbor Airport	Bar Harbor, ME
BTV	Burlington International Airport	Burlington, VT
BUF	Greater Buffalo International Airport	Buffalo, NY

Table A-1. Corridor and Feeder Airports (Continued)

Feeder Airports (Continued)

LocID	Airport Name	City, State
BWI*	Baltimore-Washington International Airport	Baltimore, MD
CHO	Charlottesville-Albemarle Airport	Charlottesville, VA
CHS	Charleston AFB/International Airport	Charleston, SC
CLE*	Cleveland-Hopkins International Airport	Cleveland, OH
CMH	Port Columbus International Airport	Columbus, OH
CRW	Charleston Yeager Airport	Charleston, WV
DTW*	Detroit Metropolitan Wayne County Airport	Detroit, MI
ELM	Elmira/Corning Regional Airport	Elmira, NY
ERI	Erie International Airport	Erie, PA
GON	Groton-New London Airport	Groton/ New London, CT
GSO	Greensboro Piedmont Triad International Airport	Greensboro, NC
HPN*	White Plains West Chester County Airport	White Plains, NY
HTO	East Hampton Airport	East Hampton, NY
HVN	Tweed-New Haven Airport	New Haven, CT
HYA	Hyannis Barnstable Municipal-Boardman/ Polando Field Airport	Hyannis, MA
IPT	Williamsport-Lycoming County Airport	Williamsport, PA
ISP*	Islip Long Island MacArthur Airport	Islip, NY
ITH	Ithaca Tompkins County Airport	Ithaca, NY
LCI	Laconia Municipal Airport	Laconia, NH
LEB	Lebanon Municipal Airport	Lebanon, NH
LNS	Lancaster Airport	Lancaster, PA
LWB	Lewisburg Greenbrier Valley Airport	Lewisburg, WV
LYH	Lynchburg Municipal-Preston Glenn Field Airport	Lynchburg, VA
MDT	Harrisburg International Airport	Harrisburg, PA
MHT	Manchester Airport	Manchester, NH
MVY	Marthas Vineyard Airport	Vineyard Haven, MA
ORF	Norfolk International Airport	Norfolk, VA
ORH	Worcester Municipal Airport	Worcester, MA
PHF	Newport News/Williamsburg International Airport	Newport News, VA
PIT*	Greater Pittsburgh International Airport	Pittsburgh, PA
POU	Poughkeepsie Dutchess County Airport	Poughkeepsie, NY
PQI	Northern Maine Regional Airport at Presque Isle Airport	Presque Isle, ME
PVC	Provincetown Municipal Airport	Provincetown, MA
PVD	Providence Theodore Francis Green State Airport	Providence, RI

Table A-1. Corridor and Feeder Airports (Concluded)

Feeder Airports (Concluded)

LocID	Airport Name	City, State
PWM	Portland International Jetport Airport	Portland, ME
RDG	Reading Regional/Carl A. Spaatz Field Airport	Reading, PA
RDU*	Raleigh-Durham International Airport	Raleigh/Durham, NC
RIC	Richmond International (Byrd Field) Airport	Richmond, VA
RKD	Rockland Knox County Regional Airport	Rockland, ME
ROA	Roanoke Regional/Woodrum Field Airport	Roanoke, VA
ROC	Greater Rochester International Airport	Rochester, NY
SBY	Salisbury-Wicomico County Regional Airport	Salisbury, MD
SCE/PSB	Philipsburg Mid-State Airport	Philipsburg, PA
SDF*	Louisville Standiford Field Airport	Louisville, KY
SYR*	Syracuse Hancock International Airport	Syracuse, NY
TTN	Trenton Mercer County Airport	Trenton, NJ
TYS	Knoxville McGhee Tyson Airport	Knoxville, TN
YHZ	Halifax, N.S., International Airport	Halifax, N.S.
YOW	Ottawa, Ont., International Airport	Ottawa, Ont.
YQI	Yarmouth, N.S., Airport	Yarmouth, N.S.
YSJ	Saint John, N.B., Airport	Saint John, N.B.
YTZ	Toronto Island, Ont., Airport	Toronto Island, Ont.
YUL	Montreal, Que., Dorval International Airport	Montreal, Que.
YYZ	Toronto, Ont., Lester B. Pearson International Airport	Toronto, Ont.

* Delay-generating Feeder Airports

7350.6D Location Identifiers, November 14, 1991

APPENDIX B

MARKET CAPTURE DATA FROM THE *PHASE II MARKET STUDY*

This appendix contains tables and figures that detail the CTR market capture data from the *Phase II Market Study*. This data was used in the *Phase II Delay Analysis* as the basis for removing fixed-wing flights and modeling the reduced fixed-wing demand that is associated with the introduction of Northeast Corridor CTR service.

For each table and figure in this appendix, the number of operations in the baseline scenario is taken from the February 8, 1990 *Official Airline Guide* (OAG) and the number of operations in the removal scenario is calculated by subtracting the number of operations in the *Phase II Market Study's* data from the number of operations in the baseline scenario.

Table B-1. 1990 Corridor Market Capture by Airport

Airport	Number of Operations in Baseline Scenario (from 2/8/90 OAG)	Number of Corridor and Feeder Operations Removed	Number of Operations in Removal Scenario	Percentage of Market Captured by CTR Service
BOS	1,152	601	551	52%
DCA	740	244	496	33%
EWR	1,037	347	690	33%
IAD	453	127	326	28%
JFK	784	129	655	16%
LGA	1,017	391	626	38%
PHL	970	339	631	35%
Total	6,153	2,178	3,975	35%

Table B-2. 1990 Feeder Market Capture by Airport

Airport	Number of Operations in Baseline Scenario (from 2/8/90 OAG)	Number of Feeder Operations Removed	Number of Operations in Removal Scenario	Percentage of Market Captured by CTR Service
ABE	93	49	44	53%
ACK	83	28	55	34%
ACY	32	21	11	66%
AIY	22	20	2	91%
ALB	358	123	235	34%
AUG	25	15	10	60%
AVP	48	24	24	50%
BBX	49	49	0	100%
BDR	65	44	21	68%
BDL*	345	88	257	26%
BGM	80	33	47	41%
BGR	71	27	44	38%
BHB	16	8	8	50%
BTV	126	38	88	30%
BUF	220	15	205	7%
BWI*	681	65	616	10%
CHO	42	9	33	21%
CHS	82	1	81	1%
CLE*	638	3	635	0%
CMH	246	1	245	0%
CRW	68	14	54	21%
DTW*	967	25	942	3%
ELM	42	26	16	62%
ERI	50	8	42	16%
GON	24	17	7	71%
GSO	140	9	131	6%
HPN*	158	69	89	44%

* Delay-Generating Feeder Airport

Table B-2. 1990 Feeder Market Capture by Airport (Continued)

Airport	Number of Operations in Baseline Scenario (From 2/8/90 OAG)	Number of Feeder Operations Removed	Number of Operations in Removal Scenario	Percentage of Market Captured by CTR Service
HTO	6	6	0	100%
HVN	22	18	4	82%
HYA	87	23	64	26%
IPT	26	9	17	35%
ISP*	112	58	54	52%
ITH	59	31	28	53%
LCI	4	4	0	100%
LEB	38	32	6	84%
LNS	28	7	21	25%
LWB	6	1	5	17%
LYH	38	8	30	21%
MDT	143	68	75	48%
MHT	99	74	25	75%
MVY	44	23	21	52%
ORF	166	29	137	17%
ORH	54	37	17	69%
PHF	54	24	30	44%
PIT*	965	3	962	0%
POU	47	22	25	47%
PQI	30	7	23	23%
PVC	6	6	0	100%
PVD	75	71	4	95%
PWM	129	67	62	52%
RDG	36	16	20	44%
RDU*	492	14	478	3%
RIC	149	28	121	19%
RKD	6	2	4	33%

* Delay-Generating Feeder Airport

Table B-2. 1990 Feeder Market Capture by Airport (Concluded)

Airport	Number of Operations in Baseline Scenario (from 2/8/90 OAG)	Number of Feeder Operations Removed	Number of Operations in Removal Scenario	Percentage of Market Captured by CTR Service
ROA	107	14	93	13%
ROC	196	18	178	9%
SBY	26	9	17	35%
SCE	38	16	22	42%
SDF*	169	1	168	1%
SYR*	264	33	231	13%
TTN	8	2	6	25%
TYS	122	6	116	5%
YHZ	191	4	187	2%
YOW	242	2	240	1%
YQI	10	4	6	40%
YSJ	50	6	44	12%
YTZ	18	14	4	78%
YUL	496	8	488	2%
YYZ	891	28	863	3%
Total	10,520	1,682	8,838	16%

* Delay-Generating Feeder Airport

Table B-3. 1990 Corridor Market Capture by Airport Pair

Airport Pair			Number of Flights in Baseline Scenario (from 2/8/90 OAG)	Number of Corridor Flights Removed	Number of Flights in Removal Scenario	Percentage of Market Captured by CTR Service
BOS	↔	DCA	53	37	16	70%
BOS	↔	EWR	49	17	32	35%
BOS	↔	IAD	12	6	6	50%
BOS	↔	JFK	47	10	37	21%
BOS	↔	LGA	68	64	4	94%
BOS	↔	PHL	46	22	24	48%
DCA	↔	EWR	22	22	0	100%
DCA	↔	LGA	62	60	2	97%
EWR	↔	IAD	20	4	16	20%
IAD	↔	PHL	6	4	2	67%
JFK	↔	PHL	46	2	44	4%
Total			431	248	183	58%

Table B-4. 1990 Feeder Market Capture by Airport Pair

Airport Pair	Number of Flights in Baseline Scenario (From 2/8/90 OAG)	Number of Feeder Flights Removed	Number of Flights in Removal Scenario	Percentage of Market Captured by CTR Service
BOS ↔ ABE	4	4	0	100%
BOS ↔ ACK	16	14	2	88%
BOS ↔ ACY	2	2	0	100%
BOS ↔ ALB	55	52	3	95%
BOS ↔ AUG	15	15	0	100%
BOS ↔ BDL	27	17	10	63%
BOS ↔ BDR	10	9	1	90%
BOS ↔ BGM	4	4	0	100%
BOS ↔ BGR	29	21	8	72%
BOS ↔ BHB	8	8	0	100%
BOS ↔ BTV	36	30	6	83%
BOS ↔ BUF	6	2	4	33%
BOS ↔ BWI	16	1	15	6%
BOS ↔ HPN	49	35	14	71%
BOS ↔ HYA	15	15	0	100%
BOS ↔ ISP	31	31	0	100%
BOS ↔ ITH	4	4	0	100%
BOS ↔ LCI	4	4	0	100%
BOS ↔ LEB	24	24	0	100%
BOS ↔ MDT	6	6	0	100%
BOS ↔ MHT	31	31	0	100%
BOS ↔ MVY	14	13	1	93%
BOS ↔ ORF	4	2	2	50%
BOS ↔ PQI	7	7	0	100%
BOS ↔ PVC	6	6	0	100%
BOS ↔ PVD	3	3	0	100%
BOS ↔ PWM	53	42	11	79%

Table B-4. 1990 Corridor Market Capture by Airport Pair (Continued)

Airport Pair			Number of Flights in Baseline Scenario (from 2/8/90 OAG)	Number of Feeder Flights Removed	Number of Flights in Removal Scenario	Percentage of Market Captured by CTR Service
BOS	↔	RIC	4	2	2	50%
BOS	↔	RKD	2	2	0	100%
BOS	↔	ROC	8	2	6	25%
BOS	↔	SYR	8	5	3	63%
BOS	↔	YHZ	4	4	0	100%
BOS	↔	YOW	4	2	2	50%
BOS	↔	YQI	4	4	0	100%
BOS	↔	YSJ	6	6	0	100%
BOS	↔	YUL	14	4	10	29%
BOS	↔	YYZ	18	12	6	67%
DCA	↔	ABE	4	4	0	100%
DCA	↔	AIY	8	8	0	100%
DCA	↔	ALB	10	6	4	60%
DCA	↔	BDL	16	4	12	25%
DCA	↔	BDR	8	8	0	100%
DCA	↔	BGM	3	3	0	100%
DCA	↔	BUF	6	1	5	17%
DCA	↔	BWI	13	11	2	85%
DCA	↔	CHS	4	1	3	25%
DCA	↔	CRW	6	6	0	100%
DCA	↔	DTW	16	1	15	6%
DCA	↔	GSO	6	1	5	17%
DCA	↔	HPN	18	14	4	78%
DCA	↔	ISP	10	10	0	100%
DCA	↔	LWB	1	1	0	100%
DCA	↔	MDT	6	6	0	100%
DCA	↔	ORF	16	16	0	100%

Table B-4. 1990 Corridor Market Capture by Airport Pair (Continued)

Airport Pair			Number of Flights in Baseline Scenario (From 2/8/90 OAG)	Number of Feeder Flights Removed	Number of Flights in Removal Scenario	Percentage of Market Captured by CTR Service
DCA	↔	PHF	8	8	0	100%
DCA	↔	PIT	12	1	11	8%
DCA	↔	ROA	5	5	0	100%
DCA	↔	SBY	7	7	0	100%
DCA	↔	SDF	4	1	3	25%
DCA	↔	TTN	2	2	0	100%
EWR	↔	ABE	16	16	0	100%
EWR	↔	AIY	12	12	0	100%
EWR	↔	ALB	26	26	0	100%
EWR	↔	AVP	12	12	0	100%
EWR	↔	BDL	25	19	6	76%
EWR	↔	BDR	11	11	0	100%
EWR	↔	BGM	10	10	0	100%
EWR	↔	BGR	6	6	0	100%
EWR	↔	BUF	22	1	21	5%
EWR	↔	BWI	20	10	10	50%
EWR	↔	DTW	30	6	24	20%
EWR	↔	ELM	10	10	0	100%
EWR	↔	GON	9	9	0	100%
EWR	↔	GSO	8	2	6	25%
EWR	↔	HVN	10	10	0	100%
EWR	↔	ITH	10	10	0	100%
EWR	↔	MDT	16	16	0	100%
EWR	↔	MHT	22	22	0	100%
EWR	↔	MVY	4	4	0	100%
EWR	↔	ORF	8	2	6	25%
EWR	↔	ORH	15	15	0	100%

Table B-4. 1990 Corridor Market Capture by Airport Pair (Continued)

Airport Pair			Number of Flights in Baseline Scenario (From 2/8/90 OAG)	Number of Feeder Flights Removed	Number of Flights in Removal Scenario	Percentage of Market Captured by CTR Service
EWR	↔	PIT	24	1	23	4%
EWR	↔	POU	1	1	0	100%
EWR	↔	PVD	28	24	4	86%
EWR	↔	PWM	12	1	11	8%
EWR	↔	RDU	12	2	10	17%
EWR	↔	RIC	8	5	3	63%
EWR	↔	ROC	20	9	11	45%
EWR	↔	SYR	18	9	9	50%
EWR	↔	YTZ	14	14	0	100%
EWR	↔	YUL	4	1	3	25%
EWR	↔	YYZ	8	8	0	100%
IAD	↔	ABE	8	8	0	100%
IAD	↔	BBX	3	3	0	100%
IAD	↔	CHO	9	9	0	100%
IAD	↔	CRW	4	4	0	100%
IAD	↔	DTW	14	8	6	57%
IAD	↔	ISP	8	8	0	100%
IAD	↔	LYH	8	8	0	100%
IAD	↔	MDT	8	8	0	100%
IAD	↔	PHF	10	8	2	80%
IAD	↔	RDG	4	4	0	100%
IAD	↔	RDU	14	8	6	57%
IAD	↔	RIC	9	9	0	100%
IAD	↔	ROA	8	8	0	100%
IAD	↔	SCE	6	6	0	100%
IAD	↔	TYS	6	6	0	100%
IAD	↔	YYZ	8	8	0	100%

Table B-4. 1990 Corridor Market Capture by Airport Pair (Continued)

Airport Pair	Number of Flights in Baseline Scenario (From 2/8/90 OAG)	Number of Feeder Flights Removed	Number of Flights in Removal Scenario	Percentage of Market Captured by CTR Service
JFK ↔ ACY	2	2	0	100%
JFK ↔ ALB	19	19	0	100%
JFK ↔ BDL	18	15	3	83%
JFK ↔ BGM	2	1	1	50%
JFK ↔ BUF	10	6	4	60%
JFK ↔ BWI	26	20	6	77%
JFK ↔ ISP	1	1	0	100%
JFK ↔ MDT	8	8	0	100%
JFK ↔ ORF	8	4	4	50%
JFK ↔ POU	11	11	0	100%
JFK ↔ PVD	14	14	0	100%
JFK ↔ RIC	4	2	2	50%
JFK ↔ ROC	10	7	3	70%
JFK ↔ SYR	14	7	7	50%
LGA ↔ ACK	16	14	2	88%
LGA ↔ ALB	20	20	0	100%
LGA ↔ BDL	30	30	0	100%
LGA ↔ BGM	7	7	0	100%
LGA ↔ BTV	11	7	4	64%
LGA ↔ BUF	16	4	12	25%
LGA ↔ BWI	10	1	9	10%
LGA ↔ CMH	10	1	9	10%
LGA ↔ CRW	2	2	0	100%
LGA ↔ DTW	22	3	19	14%
LGA ↔ ELM	8	8	0	100%
LGA ↔ GSO	8	3	5	38%
LGA ↔ HTO	6	6	0	100%

Table B-4. 1990 Corridor Market Capture by Airport Pair (Continued)

Airport Pair	Number of Flights in Baseline Scenario (From 2/8/90 OAG)	Number of Feeder Flights Removed	Number of Flights in Removal Scenario	Percentage of Market Captured by CTR Service
LGA ↔ HYA	8	8	0	100%
LGA ↔ ITH	9	9	0	100%
LGA ↔ LEB	8	8	0	100%
LGA ↔ MDT	8	8	0	100%
LGA ↔ MHT	17	17	0	100%
LGA ↔ MVY	6	6	0	100%
LGA ↔ ORF	10	2	8	20%
LGA ↔ ORH	22	22	0	100%
LGA ↔ POU	10	10	0	100%
LGA ↔ PVD	30	30	0	100%
LGA ↔ PWM	28	24	4	86%
LGA ↔ RDU	12	4	8	33%
LGA ↔ RIC	8	1	7	13%
LGA ↔ ROA	2	1	1	50%
LGA ↔ SYR	10	8	2	80%
LGA ↔ YUL	24	3	21	13%
PHL ↔ ABE	17	17	0	100%
PHL ↔ ACY	17	17	0	100%
PHL ↔ AVP	14	12	2	86%
PHL ↔ BBX	46	46	0	100%
PHL ↔ BDL	18	3	15	17%
PHL ↔ BDR	16	16	0	100%
PHL ↔ BGM	8	8	0	100%
PHL ↔ BTV	4	1	3	25%
PHL ↔ BUF	14	1	13	7%
PHL ↔ BWI	24	22	2	92%
PHL ↔ CLE	16	3	13	19%

Table B-4. 1990 Corridor Market Capture by Airport Pair (Concluded)

Airport Pair			Number of Flights in Baseline Scenario (from 2/8/90 OAG)	Number of Feeder Flights Removed	Number of Flights in Removal Scenario	Percentage of Market Captured by CTR Service
PHL	↔	CRW	2	2	0	100%
PHL	↔	DTW	21	7	14	33%
PHL	↔	ELM	8	8	0	100%
PHL	↔	ERI	8	8	0	100%
PHL	↔	GON	8	8	0	100%
PHL	↔	GSO	4	3	1	75%
PHL	↔	HPN	20	20	0	100%
PHL	↔	HVN	8	8	0	100%
PHL	↔	IPT	9	9	0	100%
PHL	↔	ISP	8	8	0	100%
PHL	↔	ITH	8	8	0	100%
PHL	↔	LNS	7	7	0	100%
PHL	↔	MDT	16	16	0	100%
PHL	↔	MHT	7	4	3	57%
PHL	↔	ORF	10	3	7	30%
PHL	↔	PHF	8	8	0	100%
PHL	↔	PIT	21	1	20	5%
PHL	↔	RDG	12	12	0	100%
PHL	↔	RIC	12	9	3	75%
PHL	↔	SBY	2	2	0	100%
PHL	↔	SCE	10	10	0	100%
PHL	↔	SYR	8	4	4	50%
Total			2,254	1,682	572	75%

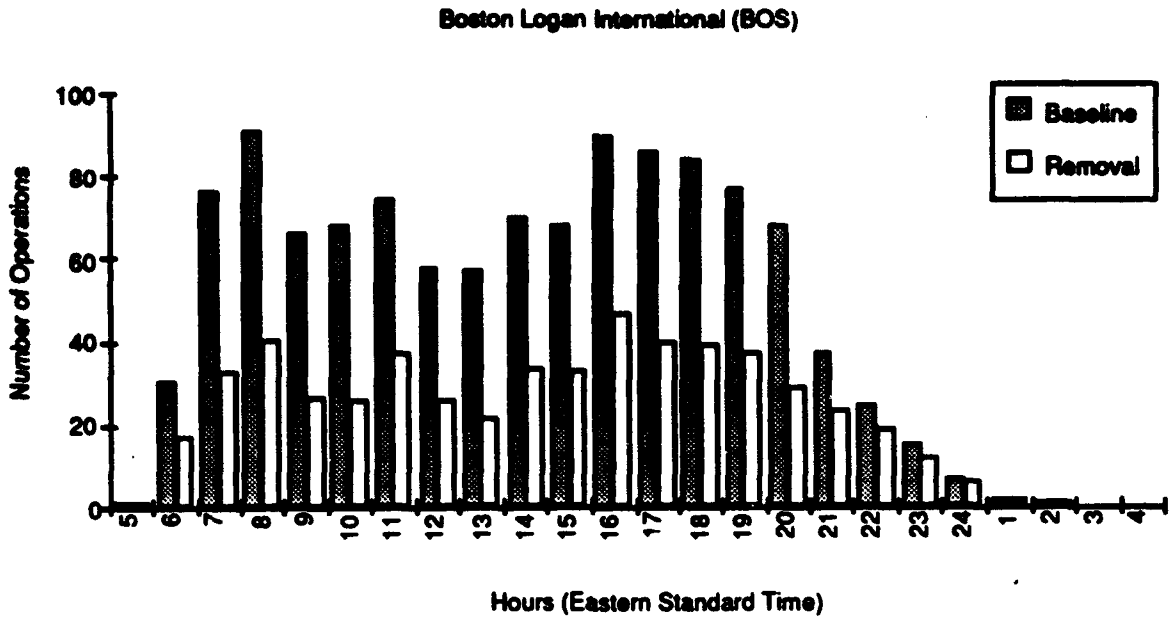


Figure B-1a. 1990 Hourly Carrier Demand at Corridor Airports

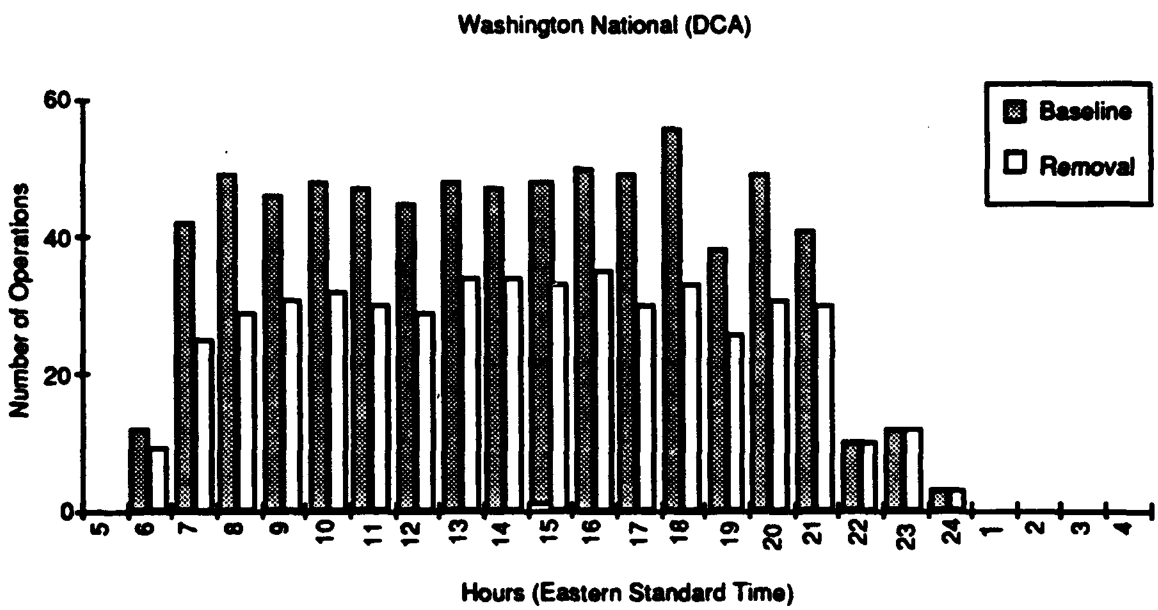


Figure B-1b. 1990 Hourly Carrier Demand at Corridor Airports

Newark International (EWR)

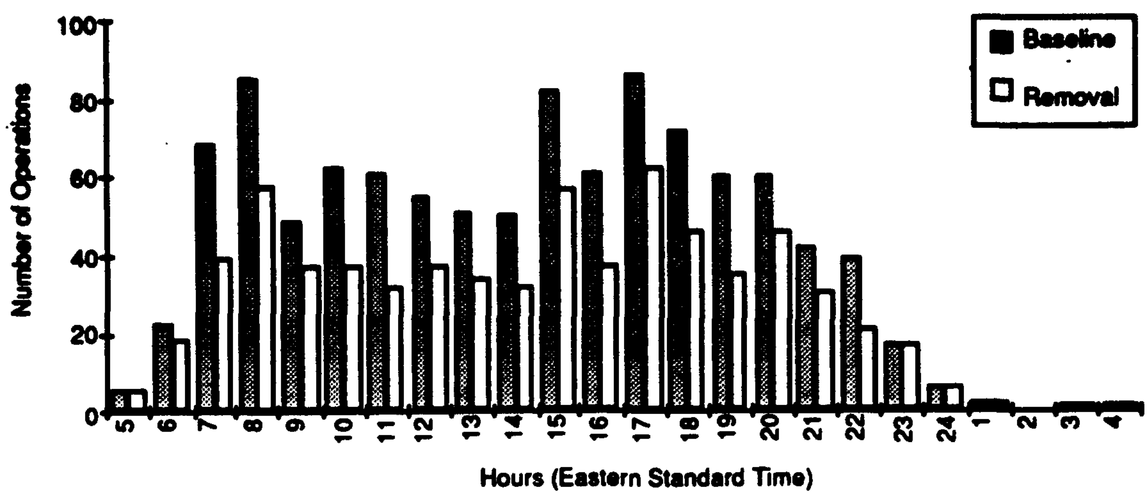


Figure B-1c. 1990 Hourly Carrier Demand at Corridor Airports

Washington Dulles International (IAD)

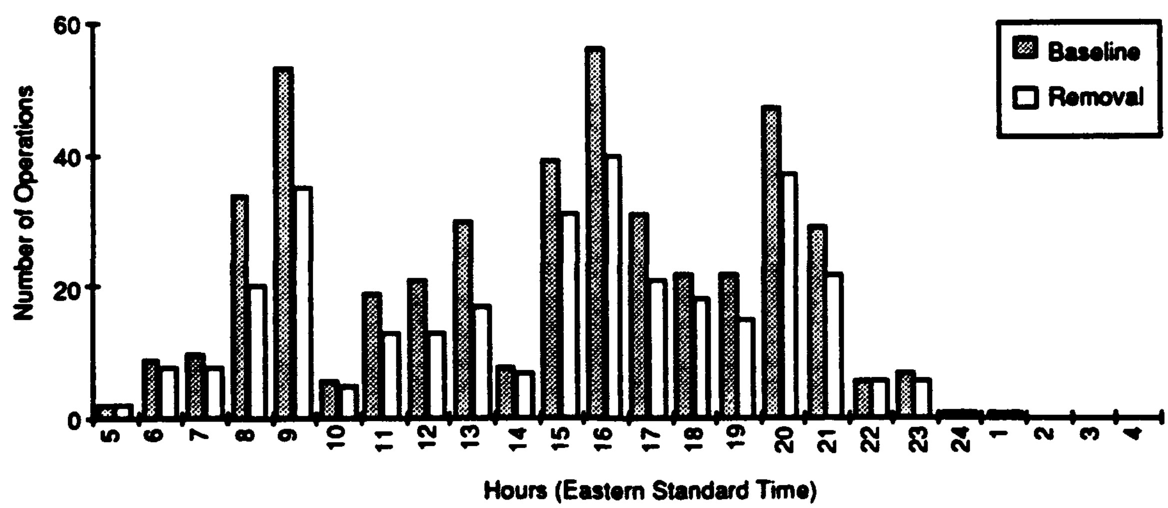


Figure B-1d. 1990 Hourly Carrier Demand at Corridor Airports

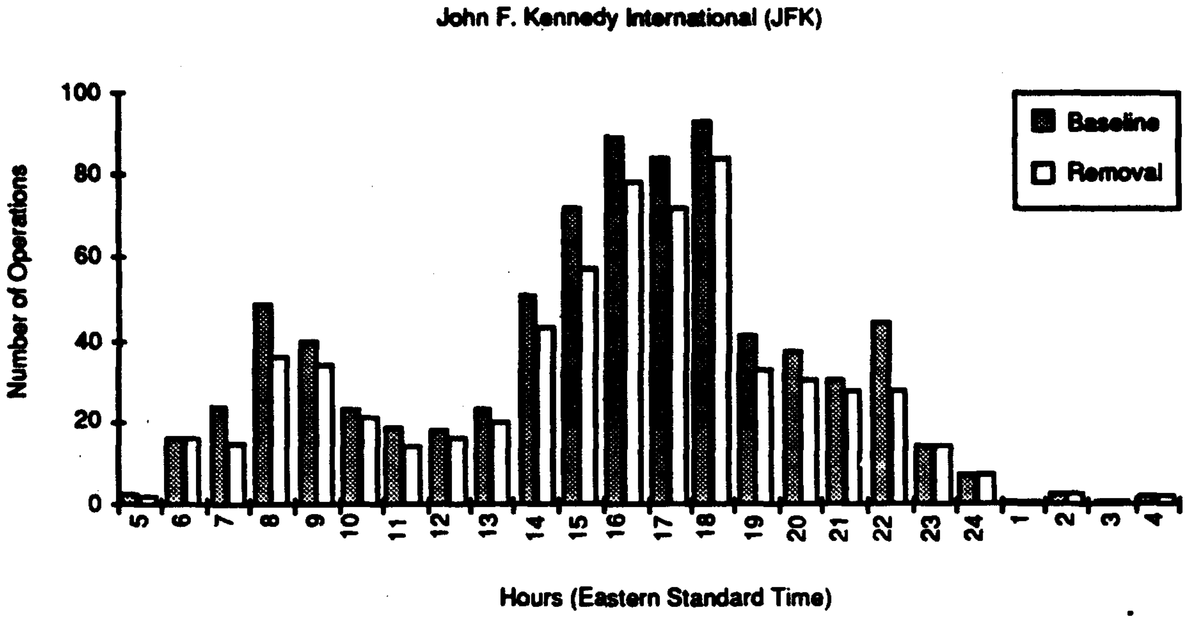


Figure B-1e. 1990 Hourly Carrier Demand at Corridor Airports

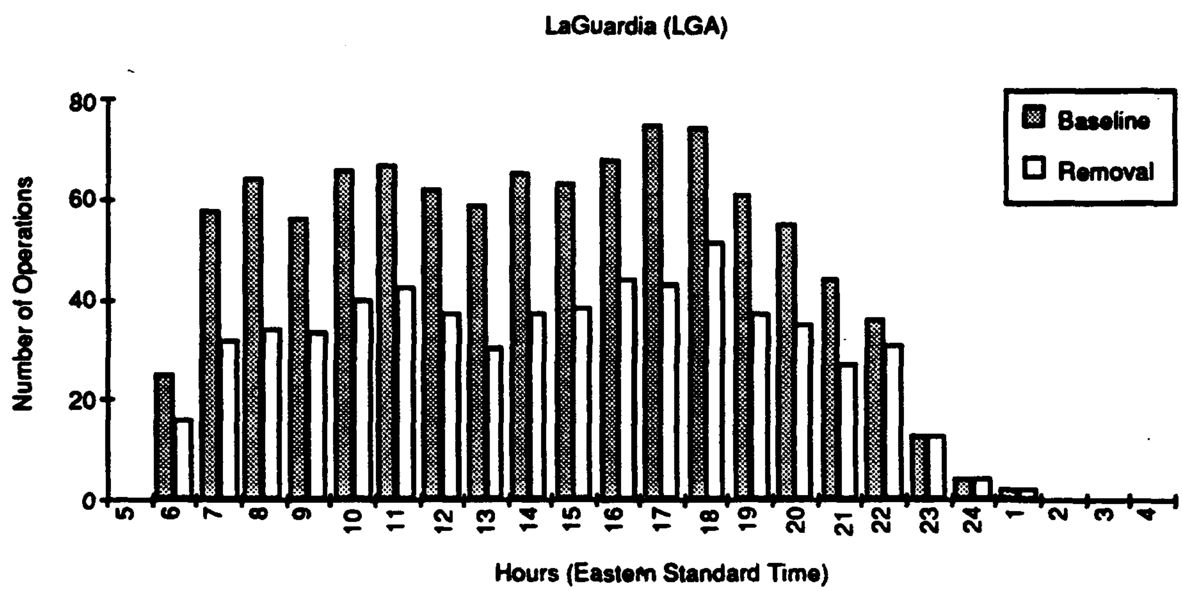


Figure B-1f. 1990 Hourly Carrier Demand at Corridor Airports

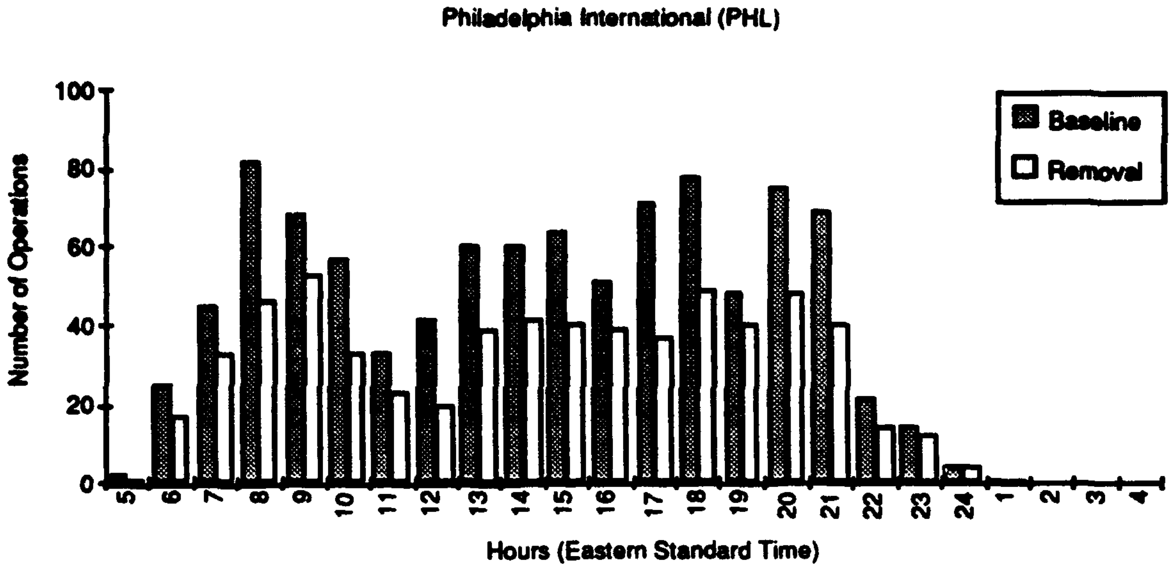


Figure B-1g. 1990 Hourly Carrier Demand at Corridor Airports

APPENDIX C

METHODOLOGY DETAILS

C.1 THE NATIONAL AIRSPACE SYSTEM PERFORMANCE ANALYSIS CAPABILITY (NASPAC) SIMULATION MODELING SYSTEM (SMS)

The NASPAC SMS is an event-step simulation that models aircraft as they move through the NAS. Events modeled for each flight include pushback from the departure gate, takeoff, fix crossing, en route flow restriction crossing, en route sector crossing, landing, and arrival at the destination gate. The SMS is composed of the simulation model itself and other software tools used to develop input data files, detailed reports, and graphical displays from the simulation output.

Modeled entities include the following Air Traffic Control (ATC) resources: airports, fixes, en route flow restrictions, and sectors. Inputs to the model include capacities for all of these entities.

Air traffic demand on the system and airspace geometry are also principal inputs to the model.

Because the model is designed to study NAS system performance issues and not local improvements in detail, airports are modeled at the aggregate level. That is, runways, taxiways, gates, and other elements of the airport system are not explicitly modeled in the simulation. However, the effects of ground delay programs are modeled explicitly.

In the NAS, the capacities of airports, fixes, and sectors may vary with time; this is also true of modeled entities in the simulation. Capacity values can vary to reflect changing weather conditions or control strategies. For the airports modeled as delay-generating entities, airport capacities are also expressed as a range of arrival and departure capacity values that vary according to arrival and departure demand. An algorithm in the simulation dynamically determines the appropriate arrival and departure capacity values for a given mix of arrival and departure demand. In the *Phase II Delay Analysis*, 58 airports were modeled as delay-generating entities.

Each of the events represented in the model is an abstraction of a real-world event; that is, no attempt has been made to accurately capture all of the subtle details associated with each activity, only the relevant aspects that materially affect NAS performance at an appropriate level of detail. For example, specific aircraft maneuvers performed in response to control instructions to ensure separation over airspace fixes are not explicitly modeled, although their effects are reflected in fix delays.

The effects for all controlled flights are modeled, although detailed statistics are calculated only for the scheduled and unscheduled flights departing from and arriving at airports represented in the model. Scheduled demand for all airports in the NAS is derived from actual scheduled flights listed in the OAG.

Unscheduled demand (i.e., general aviation and military flights) is derived from two sources:

- Instrument flight rules (IFR) flights in Host Z Data (operational data recorded by Host computers in the air traffic control centers; this data includes flight plan information and track update data for controlled aircraft as they move through the NAS)

- Visual flight rules (VFR) flights in historical data (for airports modeled as delay-generating entities)

Flight times are derived from Host Z Data and are a function of several parameters including the total distance flown, the aircraft type, and the general compass bearing between city pairs. This information is used to determine the flight time and incorporate a random element to recreate random variations present in the original data. Model inputs representing capacities, delay programs, or demand can then be modified to represent the effects of changes to different parts of the NAS.

Air carrier aircraft generally fly several flight legs over the course of a day. If an aircraft arrives late on a flight leg, that delay may be passed on to the next leg (and so on) and continue to accumulate throughout the day. In the model, individual flight legs for each aircraft are organized into an itinerary (i.e., sequence of airports visited during the simulated day) to capture this accumulation of delay.

The principal output from the model include throughput and delay at each of the airports modeled as delay-generating entities and at the fixes, sectors, and restrictions. NAS-wide totals of throughput and delay are also major outputs of the model. Two types of delay are measured. The first type, "technical delay," is delay incurred by an aircraft while waiting to use an ATC resource. For example, an aircraft that must wait its turn to depart accumulates technical delay. The second type, "effective arrival delay," measures the difference between the time an aircraft arrives at the gate in the simulation and its scheduled arrival time. It is a measure of aircraft lateness, often caused in part by the "ripple effect" of delay as it is carried through from one flight leg to another in an aircraft's daily itinerary. It is the type of delay most apparent to passengers since late arrivals may result in missed connections.

C.2 WEATHER ANNUALIZATION DAYS

Table C-1 lists the days used in the NASPAC weather annualization, along with each day's respective weight.

Table C-1. NASPAC Weather Annualization Days

Weather Day	Percent VMC	Weighting Factor
January 13, 1990	95% – 100%	80.00
March 10, 1990	80% – 85%	23.75
March 31, 1990	70% – 80%	17.50
May 16, 1990	85% – 90%	86.25
September 27, 1990	90% – 95%	127.50
December 22, 1990	less than 70%	30.00

The output measures of delay for the individual weather days are combined into a weighted annual average by multiplying these measures by the appropriate weighting factor over all six weather days, summing the products, then dividing by the sum of the weights (365).

C.3 INSTRUMENT METEOROLOGICAL CONDITIONS (IMC) AND VISUAL METEOROLOGICAL CONDITIONS (VMC) AT CORRIDOR AIRPORTS

The following figures describe the distribution of IMC and VMC at the seven corridor airports. For each figure, darkened areas indicate IMC, while light areas indicate VMC.

	Eastern Standard Time																							
	AM							PM												AM				
	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4
BOS																								
EWR																								
JFK																								
LGA																								
PHL																								
DCA																								
IAD																								

Legend

- ☐ Standard Visual Meteorological Conditions
- ■ Standard Instrument Meteorological Conditions

Figure C-1a. January 13, 1990 Weather

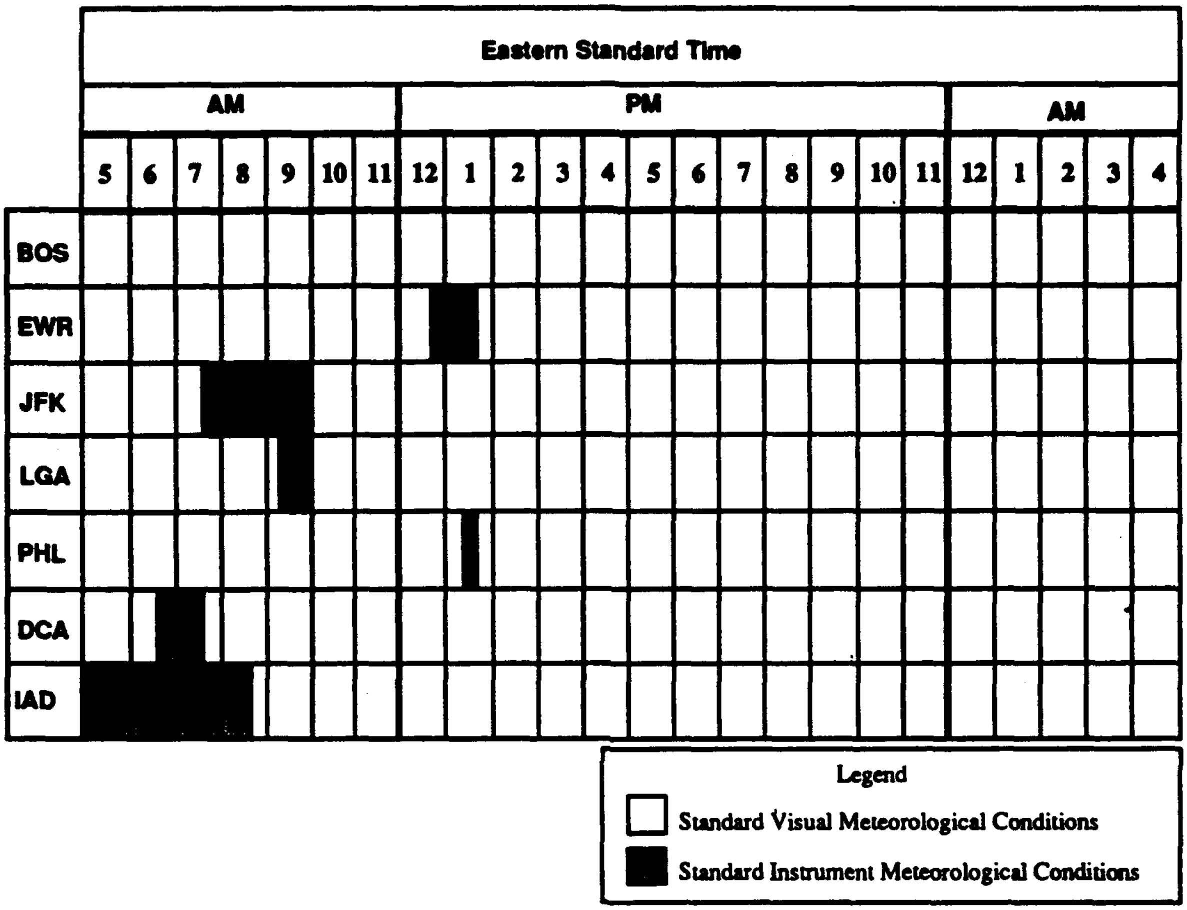


Figure C-1b. March 10, 1990 Weather

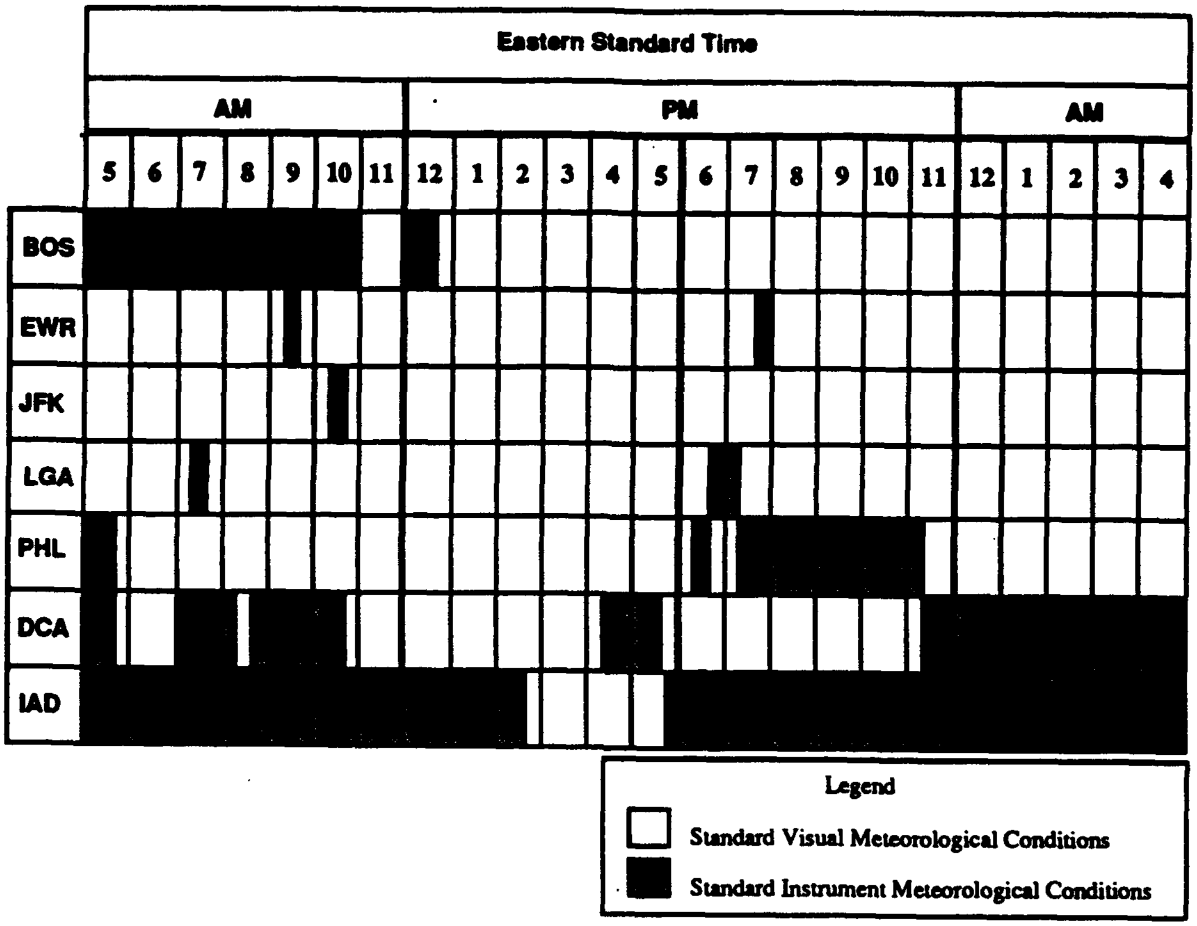


Figure C-1c. March 31, 1990 Weather

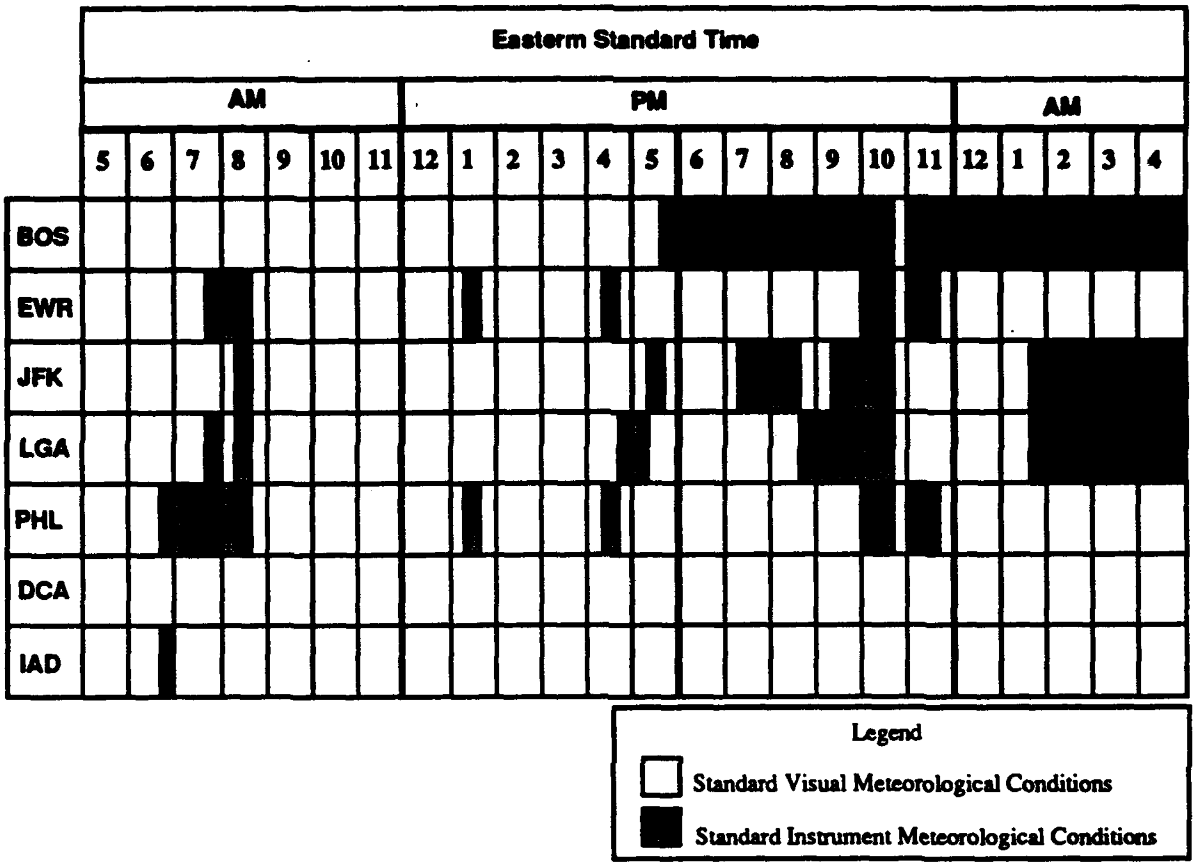


Figure C-1d. May 16, 1990 Weather

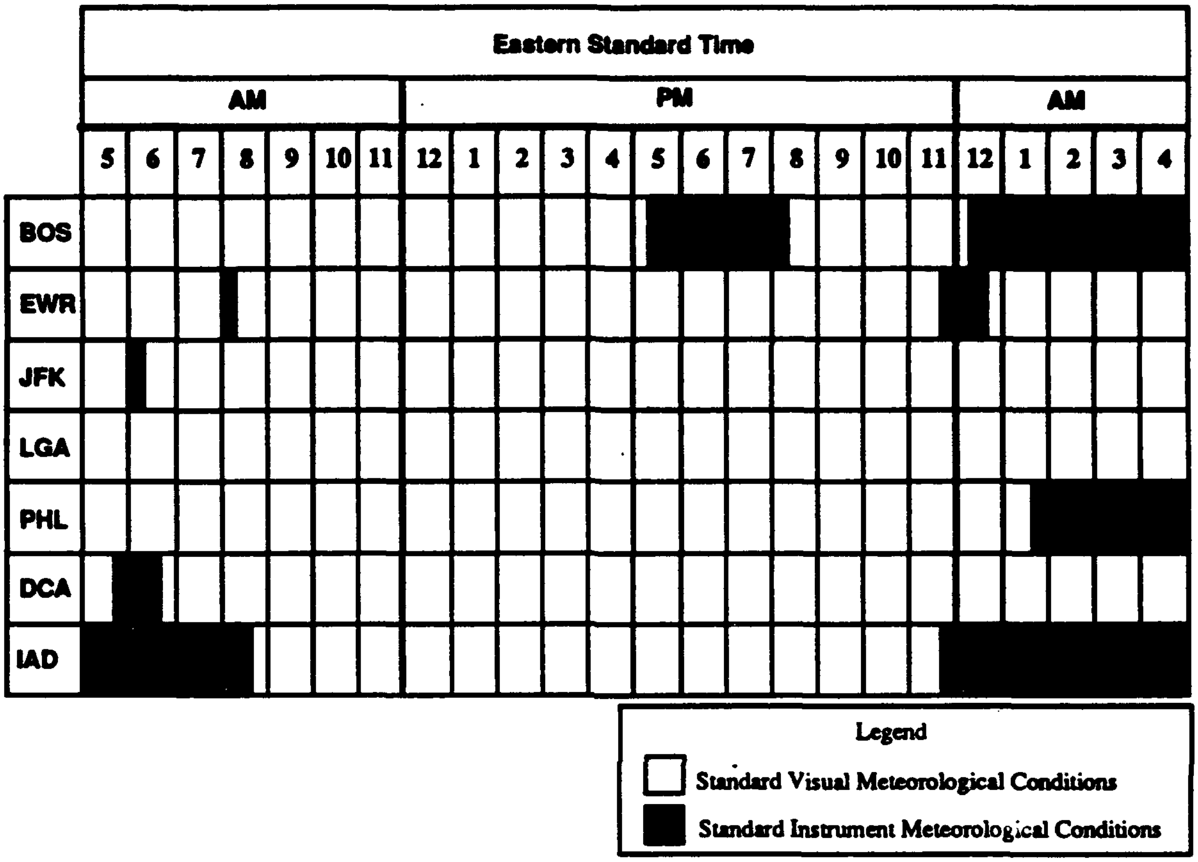


Figure C-1e. September 27, 1990 Weather

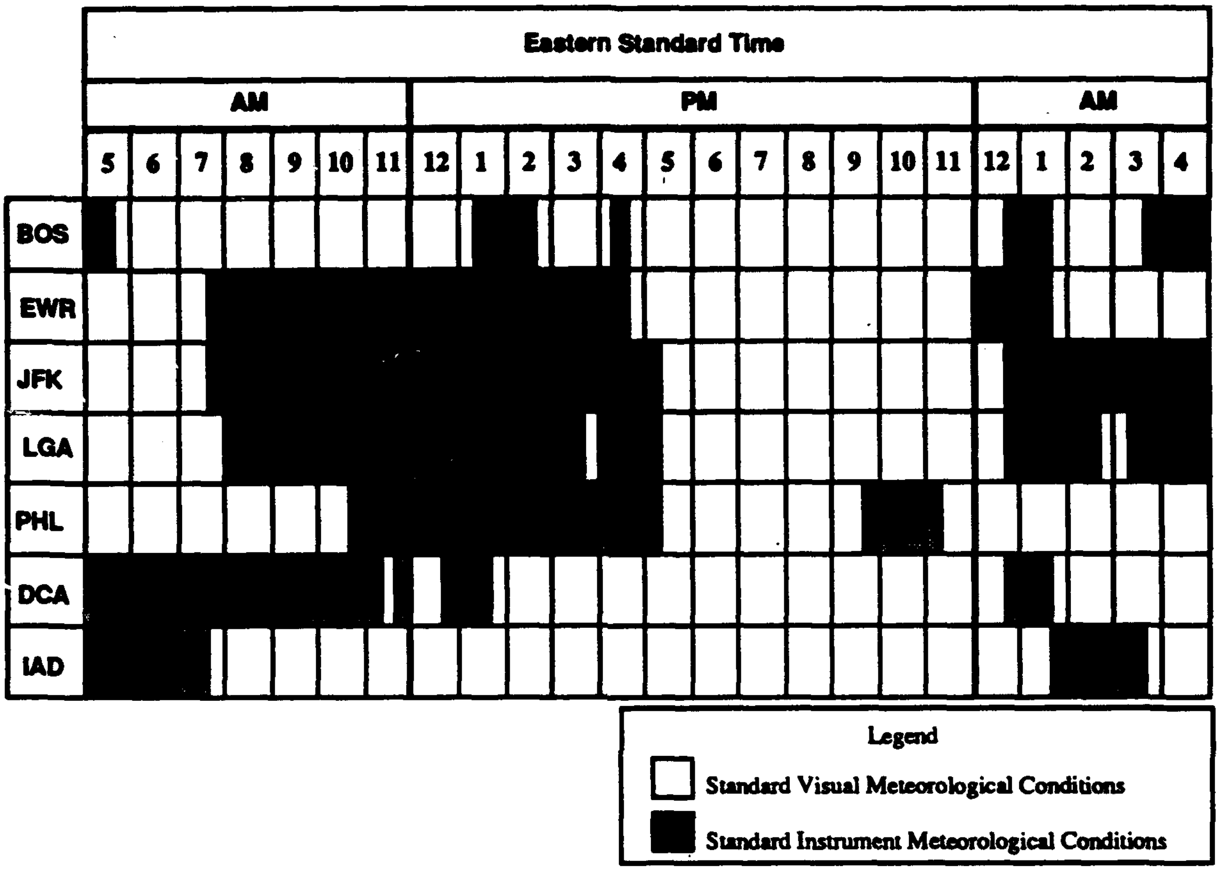


Figure C-1f. December 22, 1990 Weather

C.4 USE OF THE NASPAC FUTURE DEMAND GENERATOR

In order to assure that maximally similar comparisons were made for the year 2000 scenarios, the OAG was partitioned into two subsets, consisting of the fixed wing flights removed by CTR service and those fixed-wing flights not removed by CTR service. The two subsets were then "grown" separately, via the NASPAC future demand generator, to reflect increased demand projected for the year 2000. For the year 2000 baseline case, the TAF was applied separately to the subset of flights removed by CTR service, then to the subset of flights not removed by CTR service. For the year 2000 removal case, the TAF was applied to the subset of flights not removed by CTR service. Thus, differences in the output metrics for the year 2000 scenarios are indicative of the experimental variable, the addition of CTR service, and not of different itineraries generated for the same fixed-wing flights.

APPENDIX D

ADDITIONAL RESULTS

D.1 DEFINITIONS OF DELAY METRICS

Both delay metrics used in this report are tracked in terms of hours per year, as measured by aircraft, not by passengers. No adjustments are made for aircraft size or utilization.

Technical delay is delay incurred by an aircraft while waiting to use an ATC system resource. It is the result of congestion at a resource, and does not accumulate throughout a flight. All technical delays reported in this document are the sum of arrival and departure technical airport delays, including an airport's capacity and off-the-runway restrictions due to shared departure airspace.

Effective arrival delay measures the difference between the time an aircraft arrives at its airport gate (in the simulation) and its scheduled arrival time (from the OAG schedule). It is a measure of aircraft lateness, often caused in part by the "ripple-effect" of delay as it is carried through from one flight leg to another in an aircraft's daily itinerary. It is thus cumulative, and very dependent on the demand schedule's itinerary used in the simulation. It is the type of delay most apparent to passengers, since late arrivals may result in missed connections. Note also that it is based on a flight's itinerary and does not separately track the availability of airframe, cabin crew, and flight crew.

D.2 DELAY SAVINGS UNDER VARIOUS WEATHER CONDITIONS

Table D-1 shows the delay savings for the year 2000 under three different weather conditions. These delay savings are due to the removal of the fixed-wing flights that were identified as candidates for CTR replacement. Note that this table displays delays in terms of aircraft hours per day.

The "Annual Average" day corresponds to the results presented elsewhere in this paper, based on an average weather day. A typical "good" day is one in which the Northeast Corridor airports are under VMC for most of the day, and would typically occur 80 days out of the year. A "bad" day, which happens about 30 times per year, is one in which the Northeast Corridor airports are under IMC for much of the day.

Table D-1. Year 2000 Delay Savings Under Different Weather Conditions

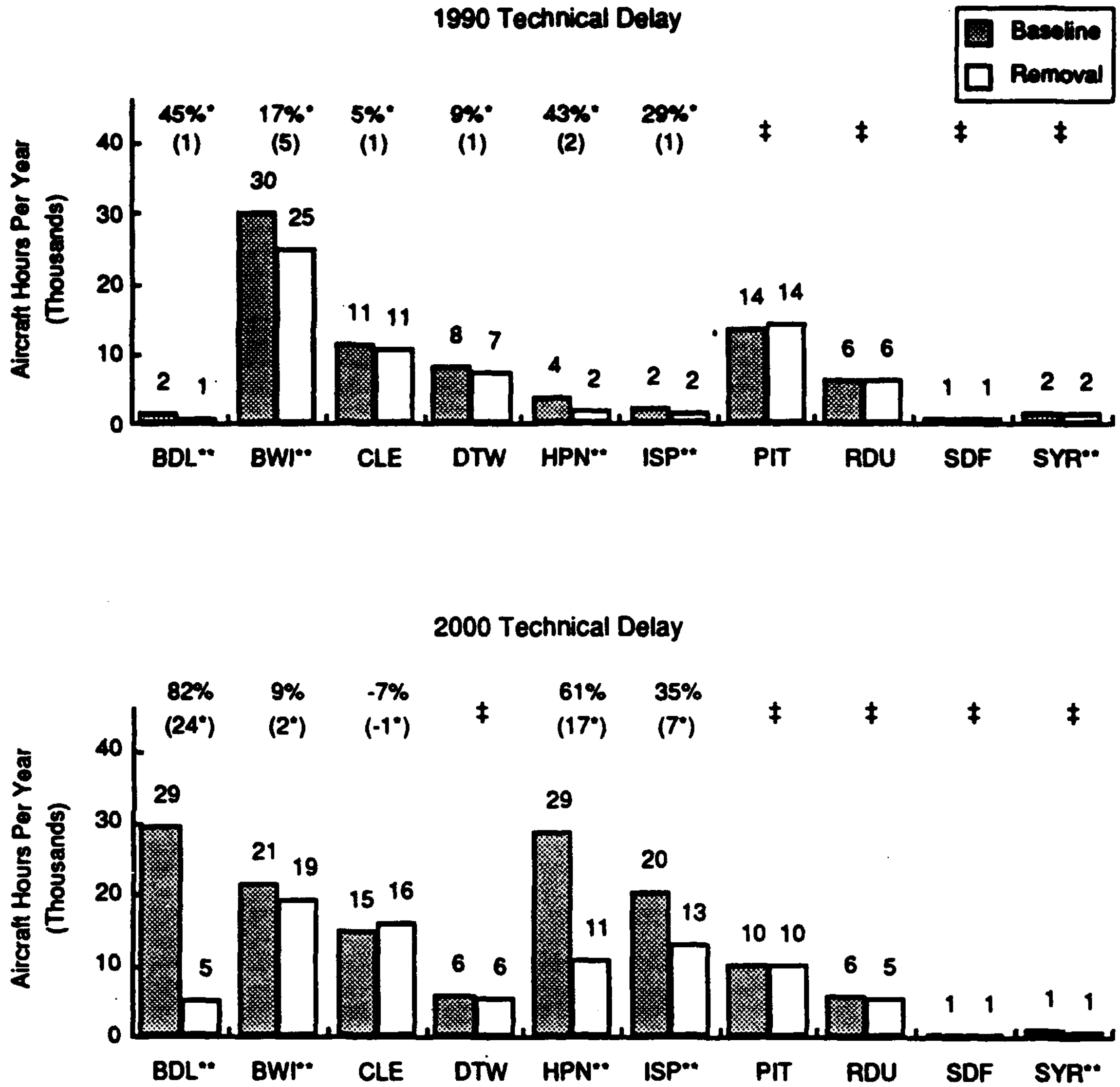
Weather Conditions	Technical Delay Savings (Hours/Day)	Effective Arrival Delay Savings (Hours/Day)
"Good" Day	1,000	1,000
Annual Average	1,500	1,800
"Bad" Day	3,200	5,900

Table D-1 shows that delays for the annual average day are not too much larger than the delays for the "good" day. The delays for the "bad" day, however, are much larger than the delays for the annual average. This is particularly true with effective arrival delays because these delays can ripple through the system, and delay problems that develop early in the day can accumulate and have a large impact on average on-time performance for the day.

D.3 FEEDER AIRPORT DELAYS

For each of the ten modeled (delay-generating) feeder airports, the effects on technical delay were measured and are shown in figure D-1. For all 69 feeder airports, effective arrival delay was measured. Figure D-2 shows the effective arrival delay benefits for the same ten airports shown in figure D-1.

The relationship between these two figures and figures 3-1 and 3-2 can be seen by aggregating the delays shown in figures D-1 and D-2. For example, the 1990 technical delay for the baseline scenario is shown in the upper chart of figure 3-1 to be 80,000 aircraft hours per year. In figure D-1, the corresponding numbers for the ten modeled feeder airports are (in thousands of hours per year) equal to 2, 30, 11, 8, 4, 2, 14, 6, 1, and 2 (which sums to 80,000 aircraft hours). Although only ten feeder airports are assumed to contribute to technical delay, all 69 contribute to effective arrival delay so the sum of the results shown in figure D-2 do not equal the summary numbers in figure 3-2.

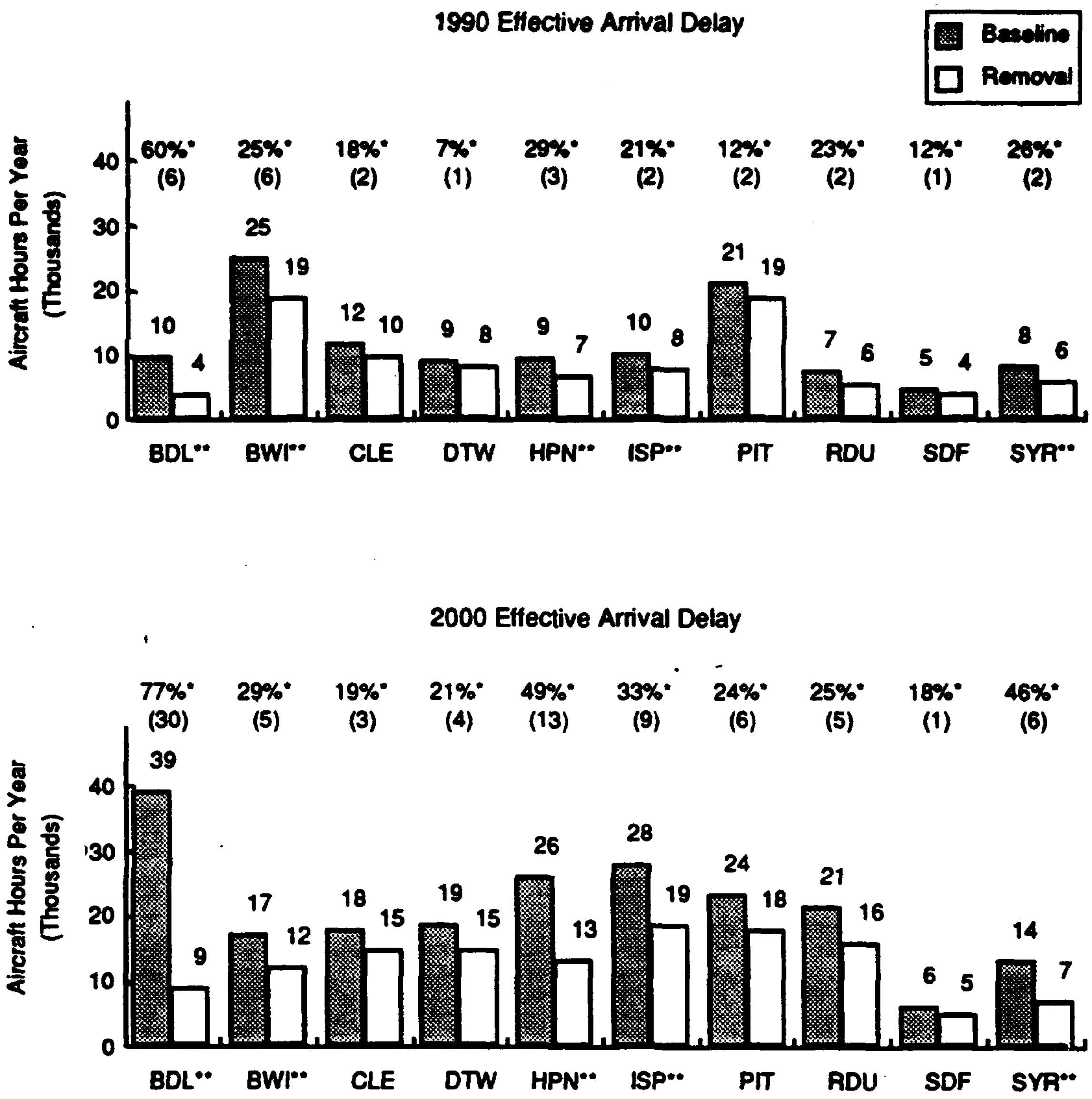


* Estimated annual delay decrease in percent and (in parentheses) aircraft hours/year due to reduction in fixed-wing operations, given *Phase II Delay Analysis* assumptions

** Market capture of scheduled traffic > 9% (others < 3%)

‡ Negligible effect on delay (rounded to nearest 1,000 hours)

Figure D-1. Technical Delay at Selected Individual Feeder Airports



* Estimated annual delay decrease in percent and (in parentheses) aircraft hours/year due to reduction in fixed-wing operations, given *Phase II Delay Analysis* assumptions

** Market capture of scheduled traffic > 9% (others < 3%)

Figure D-2. Effective Arrival Delay at Selected Individual Feeder Airports

For each of the feeder airports, the effect of reducing scheduled fixed-wing demand due to the introduction of CTR service was either a reduction in delay or a negligible effect, with only one exception.[1] In general, the airports with a substantial market capture, based on the data from the *Phase II Market Study*, reaped the largest benefits in terms of delay reduction. In particular, BDL, HPN, and ISP had the greatest fraction of flights assumed to be removed due to new CTR service and also had the greatest relative improvement in technical delay. They also were among the greatest recipients of savings in terms of effective arrival delay, along with other fairly large airports, such as BWI, PIT, RDU, and SYR.

Airports at which very little change was made in the demand pattern, referred to here as "small-market-capture" feeder airports, experienced a fairly small effect on their technical delay as a result of the introduction of CTR service. This small effect is to be expected. SYR was the only large-market-capture feeder airport for which there was a negligible effect on technical delay. It had, however, the fewest flights removed among those labeled "large-market-capture," with only 33 of 264 flights removed. In addition, over 40 percent of its traffic is non-air carrier, and thus not subject to removal, so the fraction of total traffic removed was only about six percent. Thus, its results are consistent with the general pattern of technical delays.

D.4 SUMMARY OF DELAY SAVINGS BY INDIVIDUAL AIRPORT

Table D-2 includes delay savings for all 58 airports modeled in this analysis as delay-generating airports. These include the seven corridor airports detailed in figures 3-4 and 3-5 and the ten feeder airports shown in figures D-1 and D-2.

When interpreting these results, it is important for the reader to bear in mind the discussion in section 3.6 regarding the significance of individual results. To paraphrase that discussion, the total delay benefit is more robust than individual benefits modeled at any specific airport. If itineraries change, the particular airports that benefit the most would be expected to change, but the effects themselves would still occur somewhere. The distribution of results would have been different if a different demand scenario had been used. For example, this analysis was based on demand data for an individual day in February; if a summer day had

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1 Technical delay in the year 2000 increased slightly at DTW (Detroit-Wayne County). Such a small effect is not inconsistent because the number of flights removed at DTW was very small (25 of 967) so that it is nearly like an "other" airport. At other airports, the effect on technical delay of introducing CTR service is negligible on average, but may have either a slight positive or negative effect at individual airports. A positive effect can occur, for example, if reduced delays at origin airports cause more flights to arrive on time at a particular destination, increasing the delay impact of a scheduled "surge" of arriving traffic at that destination.

been used, there may have been a smaller effective arrival delay benefit at Florida airports than shows up here.

In table D-2, it can be seen that there were a few instances of a negative impact on technical and effective arrival delay (often caused when more arriving traffic reach the terminal airspace on time, thereby exacerbating the delay impact of scheduled arrival "surges"). The number of such instances and the magnitudes involved were fairly small and swamped by the number of cases of delay savings. Again, there is much less significance to individual airport results at non-corridor airports than there is to the overall aggregate numbers.

Table D-2. Delay Savings for All Modeled Airports

Airport	Technical Delay Savings 1990		Technical Delay Savings 2000		Effective Arrival Delay Savings 1990		Effective Arrival Delay Savings 2000	
ABQ	0	3%	1,000	5%	0	-2%	0	0%
ATL	0	1%	-2,000	-6%	2,000	11%	7,000	17%
BDL‡	1,000	45%	24,000	82%	6,000	60%	30,000	77%
BNA	0	10%	-1,000	-11%	0	3%	0	4%
BOS*	39,000	95%	111,000	97%	27,000	85%	84,000	92%
BUR	0	4%	0	-9%	0	1%	0	-3%
BWI‡	5,000	17%	2,000	9%	6,000	25%	5,000	29%
CLE†	1,000	5%	-1,000	-7%	2,000	18%	3,000	19%
CLT	0	0%	0	-3%	1,000	8%	0	1%
CVG	0	1%	0	0%	1,000	4%	3,000	6%
DAL	0	-2%	0	-2%	-2,000	-10%	-2,000	-9%
DAY	0	6%	0	-4%	0	10%	2,000	24%
DCA*	16,000	67%	41,000	74%	12,000	59%	36,000	71%
DEN	0	-1%	-1,000	-4%	2,000	6%	6,000	13%
DFW	0	1%	-1,000	-2%	1,000	5%	5,000	12%
DTW†	1,000	9%	0	3%	1,000	7%	4,000	21%
EWR*	19,000	77%	49,000	85%	13,000	71%	32,000	80%
FLL	0	4%	0	1%	1,000	15%	5,000	26%
HOU	0	-3%	-1,000	-4%	1,000	4%	0	0%
HPN‡	2,000	43%	17,000	61%	3,000	29%	13,000	49%
IAD*	9,000	53%	21,000	41%	4,000	38%	11,000	47%
IAH	0	-7%	0	2%	1,000	9%	3,000	15%
IND	0	1%	0	0%	1,000	8%	2,000	16%
ISP‡	1,000	29%	7,000	35%	2,000	21%	9,000	33%
JFK*	4,000	34%	6,000	37%	5,000	39%	8,000	49%
LAS	0	-2%	0	0%	0	1%	1,000	3%
LAX	0	0%	-1,000	-5%	2,000	5%	2,000	5%
LGA*	72,000	91%	175,000	95%	27,000	84%	84,000	92%
LGB	0	0%	0	1%	0	1%	0	0%

* Corridor airport
† Large-market-capture feeder airport (market capture of scheduled traffic > 9 percent)
‡ Small-market-capture feeder airport (market capture of scheduled traffic < 3 percent)

Table D-2. Delay Savings for All Modeled Airports (Concluded)

Airport	Technical Delay Savings 1990		Technical Delay Savings 2000		Effective Arrival Delay Savings 1990		Effective Arrival Delay Savings 2000	
MCI	0	-2%	0	-4%	1,000	9%	1,000	11%
MCO	0	-3%	0	-1%	1,000	8%	5,000	18%
MDW	0	1%	-1,000	-6%	1,000	8%	3,000	11%
MEM	0	-2%	0	-1%	0	0%	1,000	5%
MIA	0	0%	4,000	7%	1,000	4%	7,000	15%
MKE	0	6%	0	-2%	1,000	14%	3,000	15%
MSP	-2,000	-4%	-3,000	-3%	0	1%	2,000	3%
MSY	0	0%	0	4%	1,000	15%	2,000	17%
OAK	0	12%	0	2%	0	0%	0	0%
ONT	0	-1%	0	-4%	-1,000	-7%	0	-2%
ORD	-1,000	-1%	-3,000	-2%	3,000	4%	7,000	8%
PBI	0	-2%	0	-7%	1,000	9%	3,000	22%
PDX	0	3%	0	4%	-1,000	-6%	0	1%
PHL*	43,000	84%	91,000	92%	3[illegible],000	79%	54,000	82%
PHX	0	0%	0	-2%	-3,000	-5%	-1,000	-2%
PIT†	0	-3%	0	-1%	2,000	12%	6,000	24%
RDU†	0	1%	0	8%	2,000	23%	5,000	25%
SAN	0	-4%	0	0%	0	-1%	1,000	5%
SAT	0	0%	0	-1%	0	2%	0	0%
SDF†	0	2%	0	10%	1,000	12%	1,000	18%
SEA	0	1%	0	-3%	0	-2%	1,000	3%
SFO	0	1%	0	1%	0	2%	2,000	5%
SJC	0	-1%	0	-2%	0	0%	0	-1%
SLC	0	-2%	0	-1%	0	-1%	0	2%
SNA	1,000	1%	2,000	0%	0	0%	2,000	1%
STL	0	1%	-2,000	-5%	1,000	1%	1,000	2%
SYR‡	0	4%	0	12%	2,000	26%	6,000	46%
TEB	0	2%	0	3%	0	3%	1,000	7%
TPA	0	10%	0	0%	2,000	18%	5,000	26%

* Corridor airport
† Large-market-capture feeder airport (market capture of scheduled traffic > 9 percent)
‡ Small-market-capture feeder airport (market capture of scheduled traffic < 3 percent)

GLOSSARY

AOR	Operations Research Service
ARD	Research and Development Service
ATC	Air Traffic Control
CAASD	Center for Advanced Aviation Systems Development
CTR	Civil Tiltrotor
DOT	Department of Transportation
EPS	Engineered Performance Standards
FAA	Federal Aviation Administration
FAATC	Federal Aviation Administration Technical Center
IFR	Instrument Flight Rules
IMC	Instrument Meteorological Conditions
LocID	Location Identifier
MTR	MITRE Technical Report
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NASPAC	National Airspace System Performance Analysis Capability
OAG	Official Airline Guide
SMS	Simulation Modeling System
TAF	Terminal Area Forecasts
TERPS	Terminal Instrument Procedures
VFPO	Vertical Flight Program Office
VFR	Visual Flight Rules
VMC	Visual Meteorological Conditions
VNTSC	Volpe National Transportation Systems Center